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# Field Computation of an Arbitrarily-oriented Dipole Above a Layered Earth

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FIELD COMPUTATION OF AN ARBITRARILY-ORIENTED  
DIPOLE ABOVE A LAYERED EARTH

by

Hussain A. Haddad and David C. Chang

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# ABSTRACT

Both the near-zone and far-zone electromagnetic field of an arbitrary-oriented dipole above a two-layer earth surface is obtained to a high degree of accuracy using a combination of numerical and analytical computational schemes. It is shown that marked differences exist between the field structures of a vertical dipole and a horizontal dipole in the case when the observation is made on the earth surface in the plane of the dipole. The magnitude of the power flux in the near field zone is shown to have maxima and minima depending upon the thickness and the electric constants of the first-layer.

## TABLE OF CONTENTS

|   | <u>Page</u> |
|---|-------------|
| 1. Introduction . . . . .   | 1           |
| 2. Formulation of the problem . . . . .                             | 3           |
| 3. Numerical scheme . . . . .                                       | 15          |
| 4. Computation based upon asymptotic and quasi-static expansions. . | 23          |
| 4.1 Asymptotic method . . . . .                                     | 23          |
| 4.2 Quasi-static approximations . . . . .                           | 26          |
| 5. Discussion of results . . . . .                                  | 30          |
| 6. Conclusion . . . . .   | 56          |
| References . . . . .  | 57          |
| Appendix A . . . . .  | 58          |
| Appendix B . . . . .  | 61          |
| Appendix C . . . . .  | 66          |
| Appendix D . . . . .  | 73          |

# LIST OF FIGURES

| <u>Figure</u>   | <u>Page</u> |
|---|-------------|
| 1. A vertical and a horizontal dipole above a finitely conducting stratified half-space . . . . .   | 4           |
| 2. Path of integration in the complex $\alpha$ -plane . . . . .   | 16          |
| 3. A path beneath the real axis avoiding the branch point at $\alpha = 1$ and pole singularities close to the real axis . . . . .   | 17          |
| 4. (a) Location of poles and branch cuts as a function of frequency for a fixed slab width . . . . .  | 22          |
| (b) Location of poles as a function of slab width for a fixed frequency . . . . .   | 22          |
| 5. A tilted dipole above a two-layer half-space. . . . .  | 31          |
| 6. Magnitude of the vertical electrical field $E_z$ on the slab surface as a function of distance $R$ for an angle $\theta = 5^\circ$ . . . . .   | 45          |
| 7. Magnitude and direction of the normalized time-average power density distribution for a vertical dipole source (1 cm of arrow length $\equiv$ unity): $f = 300$ MHz, $\lambda = 1$ meter, $n_1 = 1.732 + i.0346$ and $n_2 = 3.1637 + i.0947$ . . . . .   | 46          |
| 8. Magnitude and direction of the normalized time-average power density distribution for a horizontal dipole source in the plane of incidence; $\phi = 0^\circ$ (1 cm of arrow length $\equiv$ unity): $f = 300$ MHz, $\lambda = 1$ meter, $n_1 = 1.732 + i.0346$ and $n_2 = 3.1637 + i.0947$ . . . . . | 48          |
| 9. Magnitude and direction of the normalized time-average power density distribution in the plane perpendicular to the dipole; $\phi = 90^\circ$ , (1 cm of arrow length $\equiv$ unity): $f = 300$ MHz, $\lambda = 1$ meter, $n_1 = 1.732 + i.0346$ and $n_2 = 3.1637 + i.0947$ . . . . .              | 49          |
| 10. Magnitude of the normalized time-average power density on the slab surface as a function of observation distance for a vertical dipole ( $\phi = 0^\circ$ ), a horizontal dipole ( $\phi = 0^\circ$ ) and a horizontal dipole ( $\phi = 90^\circ$ ) . . . . .                                       | 50          |
| 11. Tilt angle of the time-average Poynting vector on the slab surface versus the normalized radial distance for a vertical dipole ( $\phi = 0^\circ$ ), a horizontal dipole ( $\phi = 0^\circ$ ) and a horizontal dipole ( $\phi = 90^\circ$ ). . . . .  | 51          |

| <u>Figure</u>  | <u>Page</u> |
|--|-------------|
| 12. Magnitude of the normalized time-average power density<br>on the slab surface for a horizontal dipole source<br>observed in the plane of incidence ( $\phi = 0^\circ$ ) . . . . .                    | 53          |
| 13. Magnitude of the normalized time-average power density on<br>the slab surface for a vertical dipole source . . . . .   | 54          |
| 14. Magnitude of the normalized time-average power density on<br>the slab surface for a horizontal dipole source<br>observed in the plane perpendicular to the dipole<br>( $\phi = 90^\circ$ ) . . . . . | 55          |
| 15. A flow chart of the computer program . . . . .   | 67          |
| 16. A flow chart of the root finder . . . . .  | 69          |

## 1. Introduction

Investigation of VHF and UHF performance of thin wire structures in the presence of a realistic ground environment is important in EMP simulation as well as other antenna applications [Baum, 1972]. Since the earth is not very conductive in these frequency ranges, effect of the ground reflection can no longer be accounted for by the structure's mirror image. In some cases, wire structures large compared with the free-space wavelength, are actually placed on the top of a prepared ground surface such as a non-reinforced concrete slab of finite thickness. The problem of finding the scattered field is then further complicated by the fact that the slab can now provide a physical mechanism for energy to spread out in the lateral direction in the form of a lossy surface-wave.

As a first step leading to the better understanding of this problem, we shall discuss in this report the development of a numerically-efficient scheme for computing electromagnetic fields produced by an arbitrarily oriented electric dipole source located in air over a multi-layered, dissipative half-space. Typically, the medium consists of only two layers with a top layer being a concrete slab of finite thickness and the bottom layer, a homogeneous earth of infinite extent. To be able to obtain all the electric and magnetic field components accurately and efficiently in both the near-field and the far-field regions is important, due to the fact that an integral equation formulation of a thin-wire structure can usually be constructed once the field components produced by individual dipole sources are known.

In what follows, we shall discuss first the spectral representation of the scattered field due to a horizontally-stratified half-space using an



approach similar to that of Wait's [1966]. We then proceed to discuss a numerical scheme for the computation of the so-called Sommerfeld integrals. Since all six field components are needed, a method is developed for simultaneous integration of these components. Also investigated is the choice of possible paths of integration, with specific reference made to the work of Lytle and Lager [1974, 1975] which finds the field components of a homogenous half-space. In addition to the numerical integration, we shall also discuss the appropriate asymptotic and near-zone expansions of each field component. They are then incorporated into the computer program in order to improve the computational efficiency. A related work in this case is that of Tsang and Kong [1974] where various asymptotic evaluations of the longitudinal magnetic field were found for a horizontal dipole placed on a lossy dielectric slab, having a thickness in the order of a few wavelengths. However, their computation was restricted to observation on the slab surface. Also included in the report is a comparison of the numerical results with various known special cases.

## 2. Formulation of the problem

Figure 1 shows a tilted electric Hertzian dipole above a finitely conducting stratified half space. This dipole is placed in the x-z plane at  $(0,0,h_0)$  making an angle  $\theta'$  with respect to the vertical z-axis; the prime refers to the source coordinate system;  $h_0$  represents the height of the dipole above the surface of the layered earth. The dipole can be decomposed into two components; one parallel to the earth surface along the x-axis with a current moment  $Idx'$  and another perpendicular to the earth along the z-direction with a current moment of  $Idz'$ . Contribution to the electromagnetic field from both dipoles can be formulated in terms of the electric Hertzian potential  $\bar{\pi}$  which consists of  $\pi_x$  and  $\pi_z$ . In this report only the derivation leading to the expressions for field produced by a horizontal dipole will be demonstrated. We also note that the method follows a somewhat different approach than the one derived by Wait [1966] even though the two solutions are formally the same.

For a horizontal Hertzian dipole, the scattered field in the  $m^{\text{th}}$ -layer can be written in terms of  $\pi_{x,m}^s$  and  $\pi_{z,m}^s$ , which has the following form:

$$\pi_{x,m}^s = (Q_0/n_m^2) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Phi_{x,m}(\xi, \eta) \exp[-\gamma_0 H_0 + i(\xi X + \eta Y)] d\xi d\eta \quad (1)$$

$$\pi_{z,m}^s = (ik_0 Q_0/n_m^2) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \xi \Phi_{z,m}(\xi, \eta) \exp[-\gamma_0 H_0 + i(\xi X + \eta Y)] d\xi d\eta \quad (2)$$

$$m = 1, 2, \dots, M$$

where  $\gamma_0 = (\xi^2 + \eta^2 - 1)^{\frac{1}{2}} = -i(1 - \xi^2 - \eta^2)^{\frac{1}{2}}$ ;  $n_m^2 = \epsilon_{rm} + i\sigma_m/(\omega\epsilon_0)$ ,

$n_m$ ,  $\epsilon_{rm}$  and  $\sigma_m$  are the refractive index, relative permittivity

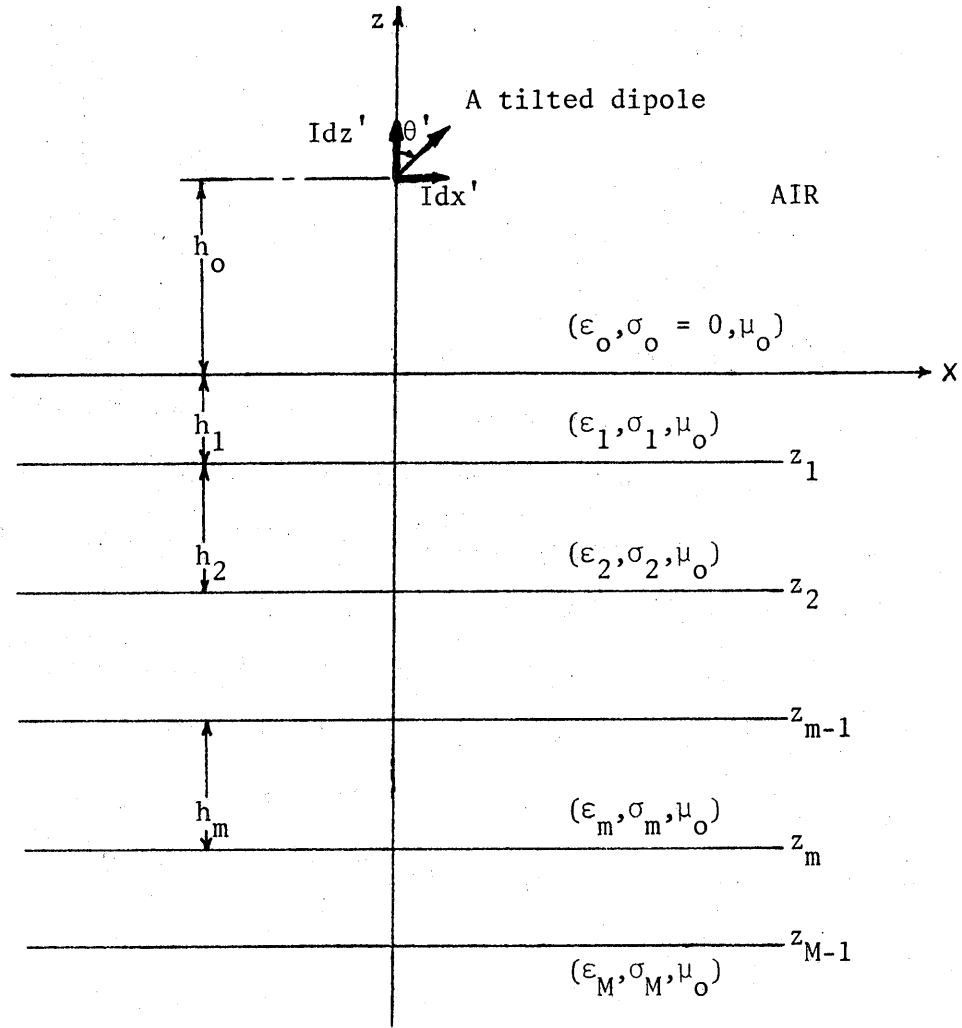


Figure 1: A vertical and a horizontal dipole above a finitely conducting stratified half space

and conductivity of the layered media;  $\omega$  represents the operating frequency with a suppressed time convention of  $\exp(-i\omega t)$ ;  $\epsilon_0$  is the permittivity of free space,  $Q_0 = i\zeta_0 I dx' / (8\pi^2)$  is the normalized dipole strength;  $X = k_0 x$ ,  $Y = k_0 y$  and  $H_0 = k_0 h_0$  are the normalized distances;  $\zeta_0$  and  $k_0$  represents the free space intrinsic impedance ( $= 120\pi \Omega$ ) and the propagation constant in free space respectively.

Since each component of the Hertzian potential satisfies a homogeneous wave equation of the kind:

$$(\nabla^2 + k_0^2 n_m^2) \bar{\pi} = 0$$

expression for  $\Phi_{x,m}$  and  $\Phi_{z,m}$  are then readily known

$$\Phi_{w,m}(z) = T_{w,m} \{ \exp[\gamma_m(Z + H_m)] + R_{w,m}^H \exp[-\gamma_m(Z + H_m)] \} \quad (3)$$

$$w = x, z ; \quad m = 1, 2, \dots, M$$

and  $\gamma_m = (\xi^2 + \eta^2 - n_m^2)^{1/2}$ ;  $\text{Re}(\gamma_m) \geq 0$ ;  $z = k_0 z$  and  $H_m = k_0 (h_1 + h_2 + \dots + h_m)$  are both normalized distances.

Thus, the values of  $\Phi_{w,m}(z)$  and its derivative with  $z$ ,  $\Phi'_{w,m}$  at the top surface of the  $m^{\text{th}}$  layer, i.e.  $Z = -H_{m-1}$ , are related to the values at the bottom, i.e.  $Z = -H_m$ , by the matrix given as

$$\begin{bmatrix} \Phi_{w,m} \\ \Phi'_{w,m} \end{bmatrix}_{Z = -H_{m-1}} = \begin{bmatrix} c_m & \gamma_m^{-1} s_m \\ \gamma_m s_m & c_m \end{bmatrix} \begin{bmatrix} \Phi_{w,m} \\ \Phi'_{w,m} \end{bmatrix}_{Z = -H_m} \quad (4)$$

Here, the prime denotes derivative;  $c_m = \cosh(\gamma_m H_m)$  and  $s_m = \sinh(\gamma_m H_m)$ . We now proceed to find  $\Phi_{w,m-1}$  in the  $(m-1)^{\text{th}}$ -layer from a knowledge of  $\Phi_{w,m}$  in the  $m^{\text{th}}$ -layer. The boundary conditions at the interface  $z = -h_{m-1}$  are

$$k_m^2 \pi_{w,m} = k_{m-1}^2 \pi_{w,m-1} \quad w = x, z$$

$$k_m^2 \frac{\partial}{\partial z} \pi_{x,m} = k_{m-1}^2 \frac{\partial}{\partial z} \pi_{x,m-1}$$

and

$$\frac{\partial}{\partial x} \pi_{x,m} + \frac{\partial}{\partial z} \pi_{z,m} = \frac{\partial}{\partial x} \pi_{x,m-1} + \frac{\partial}{\partial z} \pi_{z,m-1}.$$

By applying the above boundary conditions to (1), (2), (3) and (4) we can establish a matrix expression for  $\Phi_{x,m-1}$ ,  $\Phi'_{x,m-1}$ ,  $\Phi_{z,m-1}$  and  $\Phi'_{z,m-1}$  at one layer in terms of  $\Phi_{x,m}$ ,  $\Phi'_{x,m}$ ,  $\Phi_{z,m}$  and  $\Phi'_{z,m}$  at the adjacent layer as follows:

$$\begin{bmatrix} \Phi_{x,m-1} \\ \Phi'_{x,m-1} \\ \Phi_{z,m-1} \\ \Phi'_{z,m-1} \end{bmatrix} = \begin{bmatrix} c_m & \gamma_m^{-1} s_m & 0 & 0 \\ \gamma_m s_m & c_m & 0 & 0 \\ 0 & 0 & c_m & \gamma_m^{-1} s_m \\ \Delta_m^{-1} c_m & (\gamma_m \Delta_m)^{-1} s_m & \gamma_m \Delta_m s_m & \Delta_m c_m \end{bmatrix} \begin{bmatrix} \Phi_{x,m} \\ \Phi'_{x,m} \\ \Phi_{z,m} \\ \Phi'_{z,m} \end{bmatrix}$$

$Z = -H_{m-1} \qquad \qquad \qquad Z = -H_m$

(5)

where

$$\Delta_m = n_{m-1}^2 / n_m^2 \quad (6)$$

Thus the field at any layer interface can be obtained in terms of the field in the bottom layer, i.e. the  $M^{\text{th}}$  layer, by successive iteration.

Let us now define a transverse coupling matrix as follows:

$$\begin{bmatrix} \Phi'_{x,m} \\ \Phi'_{z,m} \end{bmatrix} = \begin{bmatrix} N_m & \tau_m \\ n_m^2 \lambda_m & n_m^2 K_m \end{bmatrix} \begin{bmatrix} \Phi_{x,m} \\ \Phi_{z,m} \end{bmatrix} \quad (7)$$

It is interesting to note that  $N_m$ ,  $K_m$  can be considered as the transverse impedance of the TE and TM-mode respectively in each layer.  $\lambda_m$  and  $\tau_m$  are the coupling coefficients of these two modes across the interface between the  $(m-1)^{th}$  and the  $m^{th}$  layer. After the substitution of (7) into (5) and then equating like coefficients for  $\Phi_{x,m}$  and  $\Phi_{z,m}$ , it is possible to obtain a relationship between the transverse coupled impedances at the  $(m-1)^{th}$  in terms of the impedances at the  $m^{th}$  layer as,

$$N_{m-1} = \gamma_m [N_m + \gamma_m \tanh(\gamma_m H_m)] / [\gamma_m + N_m \tanh(\gamma_m H_m)] \quad (8)$$

$$K_{m-1} = \beta_m [K_m + \beta_m \tanh(\gamma_m H_m)] / [\beta_m + K_m \tanh(\gamma_m H_m)] \quad (9)$$

where in the above result  $\beta_m = \gamma_m / n_m^2$ . The cross coupling terms  $\lambda_m$  and  $\tau_m$  are given by

$$\lambda_{m-1} = \lambda_m / W_m + (1 - \Delta_m^{-1}) / n_m^2; \quad \tau_{m-1} = \tau_m / W_m \quad (10)$$

where  $\Delta_m$  can be found in (6) and  $W_m$  can be written as follows:

$$W_m = [\gamma_m + N_m \tanh(\gamma_m H_m)] [\beta_m + K_m \tanh(\gamma_m H_m)] \cosh^2(\gamma_m H_m) / (\gamma_m \beta_m) \quad (11)$$

$m = 1, 2, \dots, M$

Since no reflection can occur at the bottom layer, i.e. the  $M^{th}$  layer, this implies  $R_{x,M}^H = R_{z,M}^H = 0$  in (1) and (2) then we conclude that  $N_M = \gamma_M$ ;  $K_M = \gamma_M / n_M^2$  and  $\tau_M = \lambda_M = 0$ . Therefore by using (8)-(11) the following information can be obtained;

$$N_{M-1} = \gamma_M; \quad K_{M-1} = \gamma_M / n_M^2$$

and

$$\lambda_{M-1} = 1/n_M^2 - 1/n_M^2; \quad \tau_{M-1} = 0 \quad (12)$$

Up to now, the impedances in each of the  $M$  layered earth are explicitly known via an iterative procedure based upon (8) - (12). To find the total field in the air region, we note that the electric vector potential of a horizontal dipole in the air region can be written in terms of a primary field plus a scattered one.

$$\pi_{w,0}^H = \pi_{w,0}^P + \pi_{w,0}^S \quad w = x, z \quad (13)$$

where the superscript  $H$  refers to a field due to a horizontal dipole;  $p$  and  $s$  refers to primary and scattered field, respectively, and the subscript  $o$  refers to air region.  $\pi_{x,0}^P$  and  $\pi_{z,0}^P$  are given by

$$\pi_{x,0}^P = Q_o \iint_{-\infty}^{\infty} \gamma_o^{-1} \exp[-\gamma_o |Z-H_o| + i(\xi X + \eta Y)] d\xi d\eta \quad (14)$$

$$\pi_{z,0}^P = 0 \quad (15)$$

The primary field given in (14) and (15) were obtained using the wave equation in free space with a source excitation. The scattered  $\pi_{w,0}^S$  field can be written as in (1) and (2) with  $\Phi_{w,0}$  given by

$$\Phi_{w,0} = R_{w,0}^H \exp(-\gamma_o Z) \quad w = x, z \quad (16)$$

Now by applying the boundary conditions at the interface  $z = 0$  to (1), (2), (14), (15) and (16) the following results for the reflection coefficients in free space can be obtained:

$$R_{x,0}^H = \gamma_o^{-1} (\gamma_o - N_o) / (\gamma_o + N_o) \quad (17)$$

$$R_{z,0}^H = -2\lambda_o [(\lambda_o + N_o)(\lambda_o + K_o)]^{-1} \quad (18)$$

where  $N_o$ ,  $K_o$  and  $\lambda_o$  can be found from (8)-(12) by successive iterations depending on the number of the earth layers. It can be shown that solutions for  $R_{x,o}^H$  and  $R_{z,o}^H$  are consistent with an earlier work given by Wait [1966], even though the concept associated with the coupling coefficient  $\lambda_o$  is not explicitly used in his work.

The derivation of the Hertz vector potential for a vertical dipole is much simpler because only the z-component of the Hertz potential is needed. Thus, following the same procedure previously described, we have

$$\pi_{z,o}^V = \pi_{z,o}^P + \pi_{z,o}^S \quad (19)$$

where  $V$  refers to field due to a vertical dipole and the primary field  $\pi_{z,o}^P$  is given as

$$\pi_{z,o}^P = Q_1 \iint_{-\infty}^{\infty} \gamma_o^{-1} \exp[-\gamma_o |Z-H_o| + i(\xi X + \eta Y)] d\xi d\eta \quad (20)$$

and the scattered field  $\pi_{z,o}^S$  is given by

$$\pi_{z,o}^S = Q_1 \iint_{-\infty}^{\infty} \psi_{z,o}(\xi, \eta) \exp[-\gamma_o H_o + i(\xi X + \eta Y)] d\xi d\eta \quad (21)$$

and

$$Q_1 = i\zeta_o \text{Idz}' / (8\pi^2)$$

where  $\text{Idz}'$  is the current moment for a vertical dipole.  $\psi_{z,o}$  is written as

$$\psi_{z,o} = R_{z,o}^V \exp(-\gamma_o Z)$$

and

$$R_{z,o}^V = \gamma_o^{-1} (\gamma_o - K_o) / (\gamma_o + K_o) \quad (22)$$



where  $K_o$  can be obtained from (9) by successive iterations. The total field for a tilted dipole above a finitely conducting stratified half space is then the sum of vector potentials given in (13) and (19).

$$\bar{\pi} = \bar{\pi}^H + \bar{\pi}^V \quad (23)$$

The subscript  $o$  has been dropped in the above result. Now if we write  $dx' = \sin\theta' d\ell$  and  $dz' = \cos\theta' d\ell$  and using the following identities:

$$\begin{aligned} G_{11} &= \exp(iR_{11})/R_{11} = (\frac{1}{2}\pi) \int_{-\infty}^{\infty} \gamma_o^{-1} \exp[-\gamma_o |Z-H_o| + i(\xi X + \eta Y)] d\xi d\eta \\ G_{12} &= \exp(iR_{12})/R_{12} = (\frac{1}{2}\pi) \int_{-\infty}^{\infty} \gamma_o^{-1} \exp[-\gamma_o (Z+H_o) + i(\xi X + \eta Y)] d\xi d\eta \end{aligned} \quad (24)$$

where  $R_{11} = [(Z-H_o)^2 + \rho^2]^{\frac{1}{2}}$ ;  $R_{12} = [(Z+H_o)^2 + \rho^2]^{\frac{1}{2}}$  and  $\rho = X^2 + Y^2$ , we can write  $\pi_x$  and  $\pi_z$  as follows:

$$\pi_x = C(G_{11} - G_{12} + V_2) \sin\theta' \quad (25)$$

$$\pi_z = C[(G_{11} - G_{12} + V_1) \cos\theta' + V_3 \sin\theta'] \quad (26)$$

where  $C = i\zeta_o Id\ell/(4\pi)$  and  $V_1$ ,  $V_2$  and  $V_3$  are given by

$$V_m = \int_0^{\infty} F_m(\alpha) \exp[-\gamma_o (Z+H_o)] J_o(\alpha\rho) \alpha d\alpha \quad m = 1, 2 \quad (27)$$

$$V_3 = -\cos\phi \int_0^{\infty} F_3(\alpha) \exp[-\gamma_o (Z+H_o)] J_1(\alpha\rho) \alpha^2 d\alpha \quad (28)$$

where  $J_o$  and  $J_1$  are the Bessel functions of zero and first order respectively and

$$\begin{aligned} F_1(\alpha) &= 2(\gamma_o + K_o)^{-1} \\ F_2(\alpha) &= 2(\gamma_o + N_o)^{-1} \end{aligned} \quad (29)$$

and

$$F_3(\alpha) = -2\lambda_0 [(\gamma_0 + N_0)(\gamma_0 + K_0)]^{-1}$$

In getting  $V_1$ ,  $V_2$  and  $V_3$  given in (27) and (28) we have used the following transformations:

$$x = r \cos \phi ; \quad y = r \sin \phi$$

$$\xi = \alpha \cos \phi_\alpha ; \quad \eta = \alpha \sin \phi_\alpha$$

which implies  $\xi^2 + \eta^2 = \alpha^2$  and  $\gamma_m = (\alpha^2 - n_m^2)^{\frac{1}{2}}$ ;  $\text{Re } \gamma_m \geq 0$ ,

where  $m = 0, 1 \dots M$ .

Using Maxwell equations, the electric and the magnetic fields in the air region are then obtained in terms of the vector potential  $\bar{\pi}$  according to

$$\bar{E} = \nabla(\nabla \cdot \bar{\pi}) + k_0^2 \bar{\pi} \quad (29a)$$

$$\bar{H} = -i\omega\epsilon_0 \nabla \times \bar{\pi}$$

We have listed the components  $(E_w, H_w)$ , where  $w = x, y, z$  in Table 1 and 2. Table I gives the field due to the direct contribution of the dipole, designated as  $(E_{w1}, H_{w1})$  with  $w = x, y$  or  $z$ . In order to obtain the field due to the perfect image, designated as  $(E_{w2}, H_{w2})$ , one just replaces  $R_{11}$  by  $R_{12}$  and  $(Z - H_0)$  by  $(Z + H_0)$  in Table I. In Table 2, we have written the remainder field as a sum of two parts; one contains a Bessel function of zero order  $J_0$  and the other has the Bessel function of order one  $J_1$ :

$$(E_{w3}, H_{w3}) = \sum_{m=0}^1 \int_0^\infty (\mathcal{E}_w^m, \mathcal{H}_w^m) \exp[-\gamma_0(Z + H_0)] J_m(\alpha \rho) \alpha \gamma_0^{-1} d\alpha \quad (30)$$

$m = 0, \text{ or } 1$

Table 1

|          | Horizontal Dipole  | Vertical Dipole   |
|----------|--|---|
| $E_{x1}$ | $-(1+3i/R_{11}-3/R_{11}^2)[(Z-H_0)\rho \cos \phi/R_{11}^2]G_{11} \cos \theta'$                 | $-[(1+3i/R_{11}-3/R_{11}^2)(\rho^2 \cos^2 \phi/R_{11}^2) - 1 - i/R_{11} + 1/R_{11}^2]G_{11} \sin \theta'$ |
| $E_{y1}$ | $-(3+3i/R_{11}-3/R_{11}^2)[(Z-H_0)\rho \sin \phi/R_{11}^2]G_{11} \cos \theta'$                 | $-(1+3i/R_{11}-3/R_{11}^2)(\rho^2 \sin \phi \cos \phi/R_{11}^2)G_{11} \sin \theta'$                       |
| $E_{z1}$ | $-[(1+3i/R_{11}-3/R_{11}^2)(Z-H_0)^2/R_{11}^2 - 1 - i/R_{11} + 1/R_{11}^2]G_{11} \cos \theta'$ | $-(1+3i/R_{11}-3/R_{11}^3)[(Z-H_0)\rho \cos \phi/R_{11}^2]G_{11} \sin \theta'$                            |
| $H_{x1}$ | $(i - 1/R_{11})(\rho \sin \phi/R_{11})G_{11} \cos \theta'$                                     | 0   |
| $H_{y1}$ | $-(i - 1/R_{11})(\rho \cos \phi/R_{11})G_{11} \cos \theta'$                                    | $(i - 1/R_{11})[(Z-H_0)/R_{11}]G_{11} \sin \theta'$   |
| $H_{z1}$ | 0  | $-(i - 1/R_{11})(\rho \sin \phi/R_{11})G_{11} \sin \theta'$   |

$G_{11} = \exp(iR_{11})/R_{11}$  as given in equation (24)

Table 2

| w | $\xi_w^0$   | $\xi_w^1$  |
|---|---|--|
| x | $\gamma_0 [F_2 - (F_2 - \gamma_0 F_3) \alpha^2 \cos^2 \phi] \sin \theta'$ | $\alpha \gamma_0 \{ [(F_2 - \gamma_0 F_3)/\rho] \cos(2\phi) \sin \theta' + \gamma_0 F_1 \cos \phi \cos \theta' \}$ |
| y | $-(\gamma_0 \alpha^2/2) [F_2 - \gamma_0 F_3] \sin(2\phi) \sin \theta'$    | $\alpha \gamma_0 \{ [(F_2 - \gamma_0 F_3)/\rho] \sin(2\phi) \sin \theta' + \gamma_0 F_1 \sin \phi \cos \theta' \}$ |
| z | $\gamma_0 (\gamma_0^2 + 1) F_1 \cos \theta'$                              | $\alpha \gamma_0 [\gamma_0 (F_2 - \gamma_0 F_3) - F_3] \cos \phi \sin \theta'$                                     |
| w | $\mathcal{H}_w^0$   | $\mathcal{H}_w^1$  |
| x | $-(\alpha^2 \gamma_0^2/2) F_3 \sin(2\phi) \sin \theta'$                   | $\alpha \gamma_0 [(F_3/\rho) \sin(2\phi) \sin \theta' - F_1 \sin \phi \cos \theta']$                               |
| y | $\gamma_0 [-\gamma_0 F_2 + \alpha^2 F_3 \cos^2 \phi] \sin \theta'$        | $\alpha \gamma_0 [-(F_3/\rho) \cos(2\phi) \sin \theta' + F_1 \cos \phi \cos \theta']$                              |
| z | 0   | $\alpha \gamma_0 F_2 \sin \phi \sin \theta'$   |

$$(E_{w3}, H_{w3}) = \frac{1}{\sum_{m=0}^{\infty}} \int_0^{\infty} (\mathcal{E}_w^m, \mathcal{H}_w^m) \exp[-\gamma_0 (Z+H_0)] J_m(\alpha \rho) \alpha \gamma_0^{-1} d\alpha ; F_m, m=1,2,3 \text{ are given in (29)}$$

$w = x, y, z$

Thus the total field for each component  $(E_w^t, H_w^t)$  is then given as

$$(E_w^t, H_w^t) = (E, H) \sum_{m=1}^3 (-1)^{m-1} (E_{wm}, H_{wm}) \quad w = x, y, z \quad (31)$$

where

$$E = i\zeta_0 k_0^2 (\text{Id}\ell/4\pi) \quad \text{and} \quad H = k_0^2 (\text{Id}\ell/4\pi).$$

### 3. Numerical scheme:

In this section we will discuss the numerical method used for the computation of those integrals listed in Table 2. Our primary concern is to compute all six field components for a two-layer earth representing a slab of lossy dielectric which has the electric constants of a non-reinforced concrete and is located above a homogeneous earth having electric property of a wet dirt. A typical integral form can be written as follows:

$$Q = \int_0^{\infty} T(\alpha) \alpha \gamma_0^{-1} d\alpha \quad (32)$$

where  $T(\alpha)$  is given by

$$T(\alpha) = G(\alpha) \exp[-\gamma_0 (Z + H_0)] J_m(\alpha \rho); \quad m = 0, 1$$

and  $G(\alpha)$  is a typical function listed in Table 2, which has poles and other algebraic singularities in the complex  $\alpha$ -plane. Typically the integrand in (32) has branch cut singularities due to  $\gamma_0 = (\alpha^2 - 1)^{\frac{1}{2}}$  and another due to  $\gamma_2 = (\alpha^2 - n_2^2)^{\frac{1}{2}}$ ;  $\gamma_0$  and  $\gamma_2$  are the normalized propagation constants along the  $z$ -direction for the two infinite layers  $0 \leq z < \infty$  and  $-\infty < z < -h_1$  respectively, where  $h_1$  is the width of the slab in a two layered earth media. The integration given in (32) can be split up into two parts.

$$Q = \left[ \int_0^1 + \int_1^{\infty} \right] T(\alpha) \alpha \gamma_0^{-1} d\alpha \quad (33)$$

and by using the transformation  $\tau = (1 - \alpha^2)^{\frac{1}{2}}$  in the first term of (33) and  $\tau = (\alpha^2 - 1)^{\frac{1}{2}}$  in the second term,  $Q$  can be reduced to the following form:

$$Q = i \int_0^1 T[1 - \tau^2]^{\frac{1}{2}} d\tau + \int_0^{\infty} T([1 + \tau^2]^{\frac{1}{2}}) d\tau \quad (34)$$

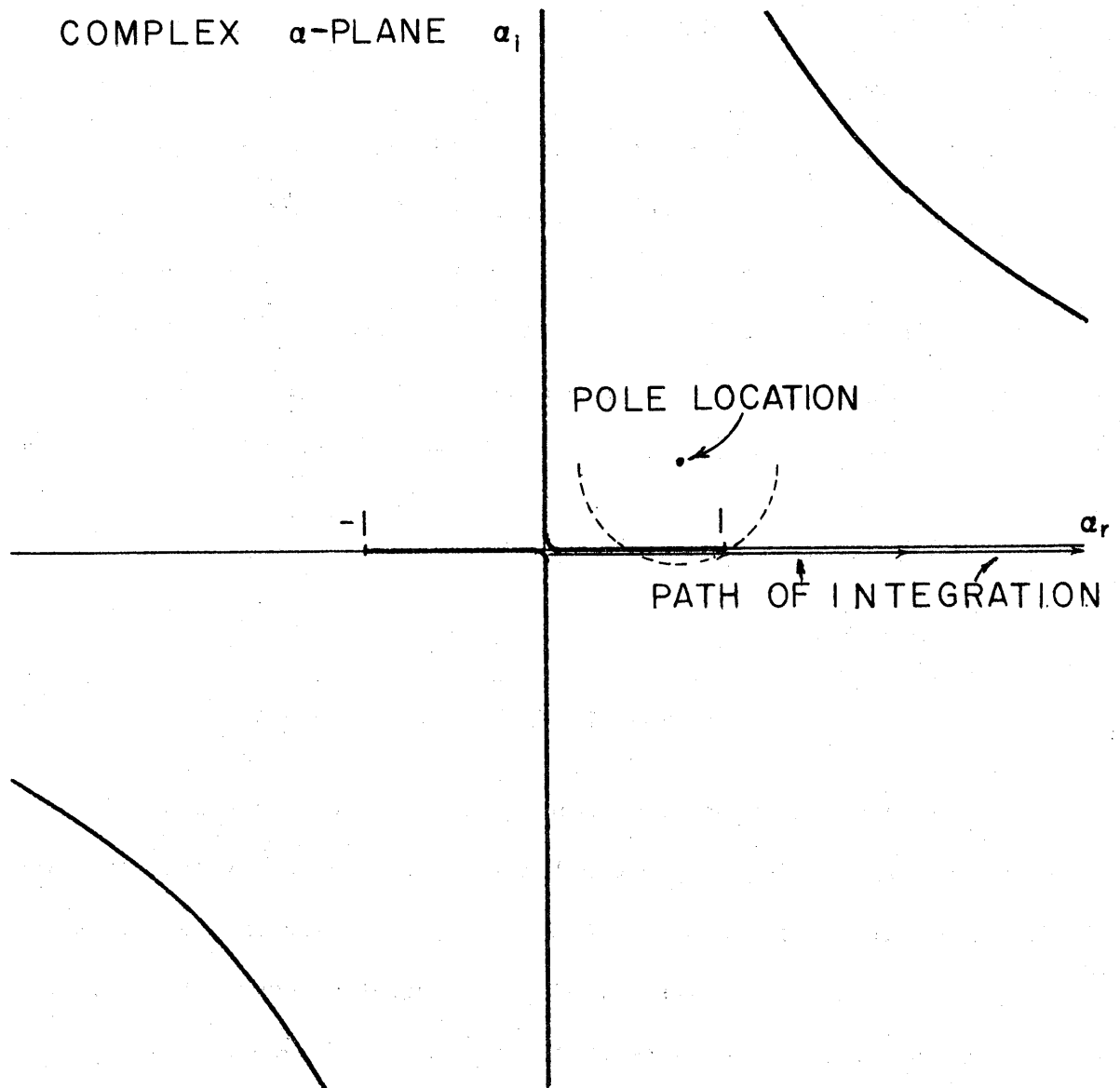


Figure 2 - Path of integration in the complex  $\alpha$ -plane

The form of  $Q$  given in (34) will be used in our computation algorithms discussed in Appendix C. We note that, in a similar work by Lytle and Lager [1974], a deformed path beneath the real axis as shown in Figure 3 was used. While such a deformation avoids the numerical difficulties arising from possible poles and other discontinuities close to the real axis, it necessitates the use of a Bessel function with complex argument. Since the value of the Bessel function grows exponentially for a large but complex argument, it appears such a deformation would not be a particularly efficient one when the horizontal distance is substantially greater than the free space wavelength unless it is very close to the real axis.<sup>†</sup>

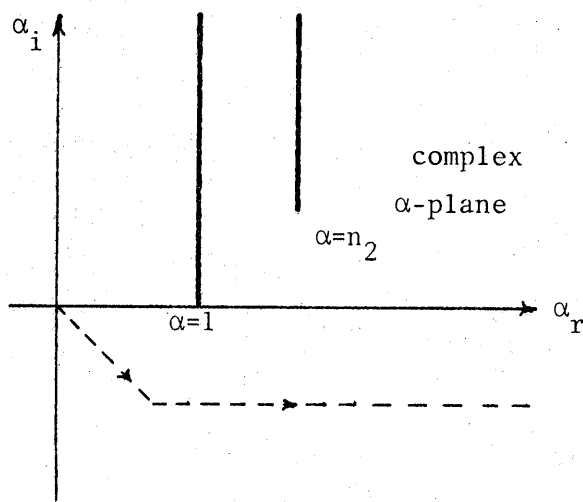


Figure 3: A path beneath the real axis avoiding the branch point at  $\alpha = 1$  and pole singularities close to the real axis.

<sup>†</sup>Lytle and Lager [1974] pointed out that one way to avoid such a problem is to use a deformed path formulation based upon a maximum decay and, or minimum oscillation criteria. Actually, the use of the steepest-descent path as a function of observation angle is another appropriate alternative [Baños, 1966; Kong, 1974]. In any case, the extension of such an approach to a multi-layered earth would involve the inclusion of contribution from possible singularities as a result of the deformation of the path.



We next consider the pole locations of  $T(\alpha)$  in the complex  $\alpha$ -plane particularly those, if any, close to the path of integration on the real axis in the range  $1 \leq \alpha_r < \infty$  (with the choice of branch cuts shown in Figure 2, pole(s) located in the range  $0 < \alpha_r < 1$  is less significant since it would have to be on the other side of the cut in the same Riemann sheet, and hence, can influence the integrand value only indirectly through the contribution around the branch point). The strategy that we have adopted is first to determine possible existence of poles, then for each pole which is close to the real axis, we would define a circle of influence within which, smaller partition of the integral is adopted to insure the accuracy of the numerical integration.

By investigating the functional form of  $T(\alpha)$  as tabulated in Table 2, it is easy to see that  $T(\alpha)$  has poles whenever the denominator of  $F_1$  or  $F_2$  vanishes. The poles of  $F_1$  can be determined from (29) as the root of the following equation:

$$\gamma_0 + K_0 = 0 \quad (35)$$

and they are the TM-type modes. The poles of  $F_2$ , on the other hand, can be found from

$$\gamma_0 + N_0 = 0 \quad (36)$$

corresponding to a set of TE-type modes.

By using the relationships given in (8) - (12) for a two-layer earth, a more explicit representation of (35) and (36) is

$$[\gamma_0 \gamma_2 H_1^2 / n_2^2 - Z^2] \tan Z + (Z / n_1^2) [\gamma_0 H_1 + \gamma_2 H_1 / n_2^2] = 0 \quad (37)$$

for the TM type modes and

$$[\gamma_0 \gamma_2 H_1^2 - Z^2] \tan Z + Z[\gamma_0 H_1 + \gamma_2 H_1] = 0 \quad (38)$$

for the TE type modes, where  $Z = i\gamma_1 H_1$  and  $H_1 = k_0 h_1$  is the normalized slab width;  $\gamma_0 H_1$  and  $\gamma_2 H_1$  are given by:

$$\gamma_0 H_1 = [-Z^2 + (n_1^2 - 1)H_1^2]^{\frac{1}{2}} = -i[Z^2 - (n_1^2 - 1)H_1^2]^{\frac{1}{2}}$$

and

$$\gamma_2 H_1 = [-Z^2 + (n_1^2 - n_2^2)H_1^2]^{\frac{1}{2}} = -i[Z^2 - (n_1^2 - n_2^2)H_1^2]^{\frac{1}{2}}$$

Thus, the problem reduces to finding the zeros of (37) and (38) in a complex  $Z$ -plane. Once found, the corresponding value in the complex  $\alpha$ -plane is then obtained from the relationship:  $\alpha = [n_1^2 - (Z/H_1)^2]^{\frac{1}{2}}$ .

It is of interest to note that (35) would reduce to the Sommerfeld pole of a half space problem whenever  $H_1 \rightarrow 0$  or  $\infty$  and (36) would have no zeros as expected since it reduces to  $(\gamma_0 + \gamma_2)$  when  $H_1 \rightarrow 0$  and to  $(\gamma_0 + \gamma_1)$  for  $H_1 \rightarrow \infty$ .

In the case of  $\sigma_2 \rightarrow \infty$  or the second earth layer is a perfect conductor, equation (37) and (38) reduces to

$$-[(n_1^2 - 1)H_1^2 - Z^2]^{\frac{1}{2}} + (Z/n_1^2)^{\frac{1}{2}} \tan Z = 0 \quad (39)$$

for the TM-type modes and

$$Z + [(n_1^2 - 1)H_1^2 - Z^2]^{\frac{1}{2}} \tan Z = 0 \quad (40)$$

for the TE-type modes. Thus for a lossless slab where  $n_1$  is a real quantity (39) and (40) represents a set of even TM-type and odd TE-type surface wave modes respectively. These real roots are then used as a starting value in

the search of the complex roots when the conductivities of earth and slab are finite. The computational technique for finding these roots is described in Appendix C.

We have plotted in Figure 4a location of the pole corresponding to the  $TM_1$ -mode over a frequency range from 100-370 MHz, for a cement slab ( $\epsilon_{r1} = 3$  and  $\sigma_1 = .002$  mho/m) of width  $h_1 = 10$  cm over a wet earth ( $\epsilon_{r2} = 10$ ,  $\sigma_2 = .01$  mho/m). As frequency increases, the pole moves upward and the branch cut moves downward. At about 400 MHz the pole disappears in the next Riemann surface. If we now reduce the slab width gradually, but fix the operating frequency at 400 MHz, as shown in Fig. 4b, the pole reappears in the proper sheet when the slab width is reduced to 9 cm, and continuously moves downward as width decreases. At  $h_1 = 0$ , it reduces to a Sommerfeld pole for a half space region.<sup>†</sup> It is noteworthy that equation (38) presents no TE-type of solution until the slab width is greater than 10 cm. In Table 3, we have tabulated the locations of both TE and TM modes for  $h_1$  ranging from 10 cm to 50 cm. It is obvious that those poles which are far away from the real axis should present no real problem for our numerical computation of the Q-integrals.

Except for the region with the possible appearance of a simple pole, the path of integration in (34) is subdivided basically according to the extent of oscillation associated with the Bessel function and the rate of decay of the exponential function in the integrand. The infinite integral is then truncated at a value of  $\tau$  where either the integral beyond that point is negligible, or an analytical approximation to the remainder is possible. Incorporation of this scheme is detailed in Appendix C.

<sup>†</sup>The disappearance, followed by a reappearance, of a slab mode was also observed earlier in related work by Schevchenko [1972].

TABLE 3

Roots as a function of slab width and frequency

| frequency<br>MHz | $h_1 = 10$ cm              | $h_1 = 20$ cm              | $h_1 = 30$ cm             | $h_1 = 50$ cm             |
|------------------|----------------------------|----------------------------|---------------------------|---------------------------|
| 100              | TM<br>.954452 + i .0378452 | TM<br>.950803 + i .0770147 | TM<br>.933858 + i .137896 | TM<br>1.14523 + i .505429 |
|                  | TM<br>.951733 + i .0728692 | TM<br>.918351 + i .298208  | _____                     | TM<br>1.52873 + i .25662  |
| 200              | _____                      | _____                      | TE<br>.981837 + i .253395 | TE<br>1.37374 + i .150405 |
|                  | TM<br>.942977 + i .13541   | _____                      | _____                     | TM<br>1.0953 + i .212372  |
| 300              | _____                      | TE<br>.986075 + i .235745  | TE<br>1.31183 + i .155028 | TE<br>1.5402 + i .0747219 |
|                  | _____                      | _____                      | _____                     | TM<br>1.60042 + i .152418 |

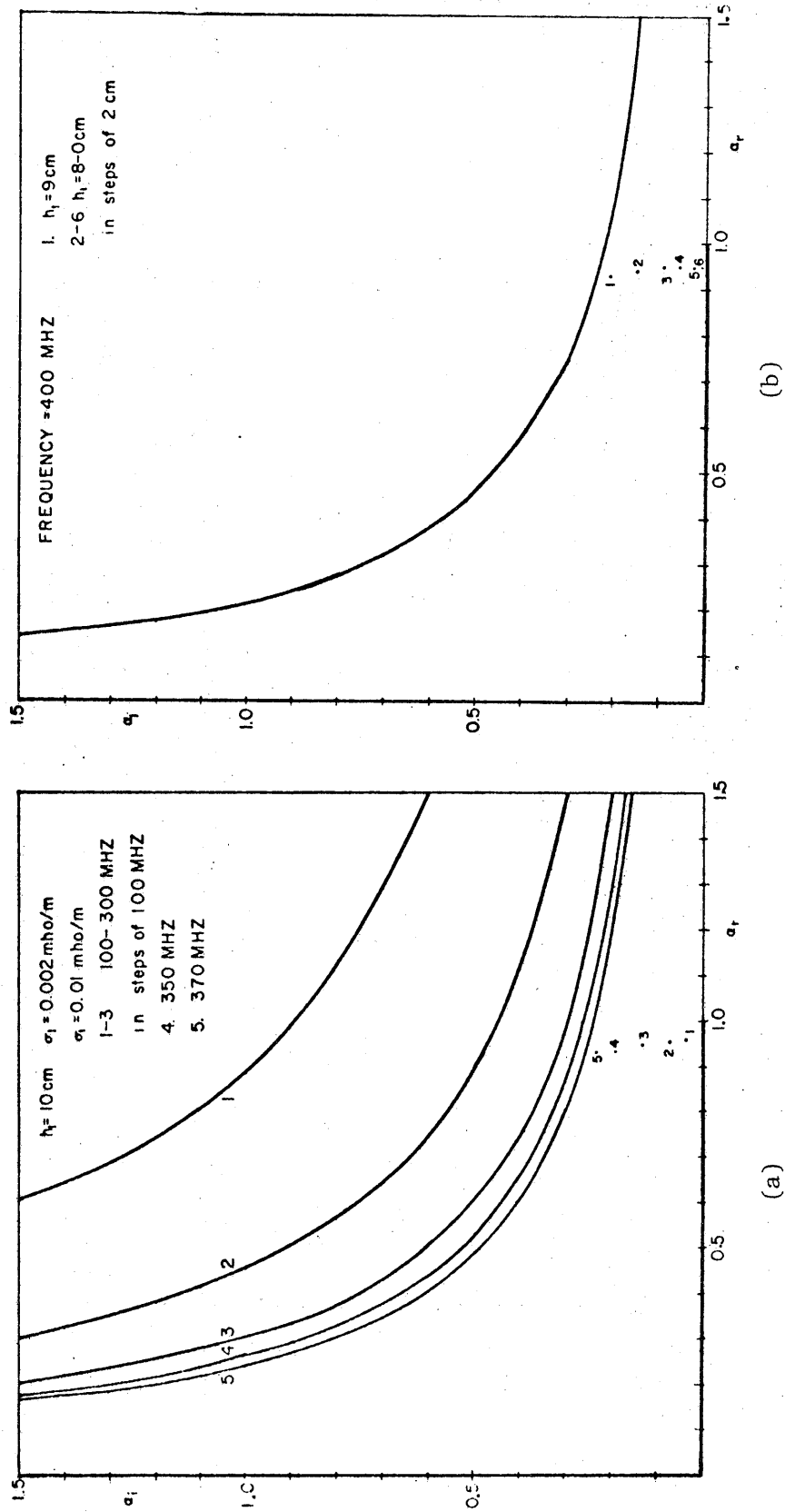


Figure 4: (a) Location of poles and branch cuts as a function of frequency for a fixed slab width.  
 (b) Location of poles as a function of slab width for a fixed frequency.

#### 4. Computation based upon asymptotic and quasi-static expansions

The numerical integration we outlined in the previous section for the functions given in Table 2, and in the case of a two-layer earth is inefficient for a very large and a very small observation distance. To improve the efficiency we need to incorporate into our numerical program an asymptotic solution for the case of a very long distance, say over 10 free space wavelengths and a quasi-static solution for the case of a very short distance, say less than .01 wavelength.

##### 4.1 Asymptotic method.

In this section we seek the asymptotic solution of a function

$\Gamma(R)$  in the form of

$$\Gamma(R) = \int_0^{\infty} G(\alpha) \exp[-\gamma_0(Z + H_0)] J_m(\alpha\rho) \alpha \gamma_0^{-1} d\alpha, \quad m = 0 \text{ or } 1 \quad (41)$$

where  $G(\alpha)$  is a typical function listed in Table 2,  $R = [(Z + H_0)^2 + \rho^2]^{\frac{1}{2}}$ .<sup>†</sup> We assume that  $G(\alpha)$  has only one simple pole at  $\alpha = \alpha_0$  sufficiently close to the path of integration. By extending the integration in (41) over the negative real axis of the complex  $\alpha$ -plane one can transform  $\Gamma(R)$  into the following form:

$$\Gamma(R) = \int_{-\infty}^{\infty} f(\alpha) e^{Rg(\alpha)} d\alpha \quad (42)$$

where

$$f(\alpha) = (\alpha \gamma_0^{-1}/2) G(\alpha) H_m^{(1)}(\alpha\rho) e^{-i\alpha\rho}, \quad m = 0, 1 \quad (43)$$

$H_m^{(1)}(\alpha\rho)$  is the Hankel function of the first kind of  $m$  order. It has been assumed that  $G(\alpha)$  is an even function of  $\alpha$  whenever the order of Bessel function  $J_m(\alpha\rho)$  is even and odd function of  $\alpha$  whenever the Bessel function order is odd.  $g(\alpha)$  is given as

<sup>†</sup> In what follows,  $R_{12}$  will be replaced by  $R$  for convenience.

$$g(\alpha) = -\gamma_0 \cos \theta + i \alpha \sin \theta \quad (44)$$

where  $Z+H_0 = R \cos \theta$ ;  $\rho = R \sin \theta$  and  $R = [(Z+H_0)^2 + \rho^2]^{\frac{1}{2}}$  is the distance from the image source of a perfect conductor half-space to the observation point and  $\theta$  is the angle that  $R$  has with the vertical  $z$ -axis.

In order to develop an appropriate asymptotic expansion, we now follow the work of Brekhovskikh [1960], by deforming the contour of integration from the real axis to the steepest descent path in the complex  $\alpha$ -plane, passing through a saddle point  $\alpha_s$  where  $g'(\alpha_s)=0$ . Assuming such a deformation yields no additional residue contribution and defining a real variable  $s$  along the steepest descent path so that  $s^2 = g(\alpha_s) - g(\alpha)$ , we have the following expression

$$\Gamma(R) = e^{Rg(\alpha_s)} \int_{-\infty}^{\infty} \Phi(s) e^{-Rs^2} ds$$

where  $\Phi(s) = f(\alpha) \frac{d\alpha}{ds}$ . From (44), it is not difficult to show that  $\alpha_s = \sin \theta$  so that  $g(\alpha_s) = i$ . Now since we have assumed the existence of a pair of poles at  $\alpha = \pm \alpha_p$  in the complex  $\alpha$ -plane, the expression  $\Phi(s)$  also possesses a pair of poles in the complex  $s$ -plane located correspondingly at  $s = \pm \beta$  where

$$\beta = [g(\alpha_s) - g(\alpha_p)]^{\frac{1}{2}} = e^{i\pi/4} [1 - (1-\alpha_p^2)^{\frac{1}{2}} \cos \theta - \alpha_p \sin \theta]^{\frac{1}{2}}$$

Thus, we can rearrange the expression for  $\Gamma(R)$  in the form of

$$\Gamma(R) = e^{iR} \int_{-\infty}^{\infty} \psi(s) \frac{e^{-Rs^2}}{s^2 - \beta^2} ds \quad (45)$$

The term  $\psi(s) = (s^2 - \beta^2) \Phi(s)$  is then a smooth function near the saddle

point  $s=0$  and therefore can be expanded in Taylor series as

$$\psi(s) = \sum_{n=0}^{\infty} \frac{C_n}{n!} s^n$$

Substitution of this expression into (45) and subsequent evaluation of the individual integrals yield the following asymptotic expression

$$\Gamma(R) = 2 \pi^{\frac{1}{2}} e^{iR} e^{-u^2} \sum_{n=0}^{\infty} \frac{C_{2n}}{4^n n! R^{n-\frac{1}{2}}} Q_{2n}(u) \quad (46)$$

where

$$Q_{2n}(u) = \int_u^{i\infty} \frac{e^{x^2}}{x^{2n}} dx$$

here  $u = \pm \beta \sqrt{R}$  and again,  $R = R_{12}$ . Typically, only two terms are used in our computation. The coefficients  $C_0$  and  $C_2$ , in this case, are known explicitly in terms of  $f(\alpha)$ ,  $g(\alpha)$  and their derivatives (Brekhovskikh [1960], and Felson and Marcuvitz [1973]);

$$\begin{aligned} C_0 &= \psi(0) = -\beta^2 \Phi(0) \\ \frac{1}{2} C_2 &= \psi''(0)/2 = -\frac{2}{f(0)} \left\{ \frac{g'''}{(g'')^2} f'(0) - \frac{f''(0)}{g''} \right. \\ &\quad \left. + \left[ \frac{1}{4} \frac{g^{IV}}{(g'')^2} - \frac{5}{12} \frac{(g''')^2}{(g'')^3} - \frac{1}{\beta^2} f(0) \right] \right\} \end{aligned}$$

Here, the primes denote derivatives with respect to  $\alpha$ . Now, since

$$\left. \frac{d\alpha}{ds} \right|_{s=0} = 2^{\frac{1}{2}} e^{-i\pi/4} \cos\theta$$

along the steepest descent path we have from (44) and the definition that  $f(\alpha)(d\alpha/ds) = \Phi(s)$  the following expression

$$C_0 = -\beta^2 (2^{\frac{1}{2}} e^{-i\pi/4} \cos\theta) f(0) \quad (47)$$



$$\frac{1}{2}C_2 = j 2^{\frac{1}{2}} e^{-i\pi/4} \cos\theta \{3\sin\theta f'(0) - \cos^2\theta f''(0) + (3/4 + j/\beta)f(0)\} \quad (48)$$

Here we note that, because the function  $f$  typically behaves like  $(\alpha_0 + \Omega)^{-1}$ , where  $\Omega$  is some slowly-varying function around  $\gamma_0 \approx 0$ , its derivatives are singular at  $\alpha=1$  even though the value of  $C_2$  is finite. Thus, in order to avoid the difficulty in numerical computation, we can define a new variable  $\alpha = \sin w$  so that

$$\begin{aligned} \frac{1}{2}C_2 = & - (1+j)\beta^2 \left\{ 2 \sin\theta \left. \frac{df}{dw} \right|_{w=\theta} - \cos\theta \left. \frac{d^2f}{dw^2} \right|_{w=\theta} \right. \\ & \left. + (3/4 + j/\beta^2)f(w=\theta) \cos\theta \right\} \end{aligned} \quad (49)$$

and  $f$  is given in (43).

#### 4.2 Quasi-Static approximation

We have mentioned earlier that the typical numerical computation of the field integral becomes very time consuming, when an observation distance is much smaller than a wavelength. Due to the slow convergence of the exponential and Bessel function the numerical computation of the integral in (30) needs to be carried out for excessively large values of  $\alpha$ .

Obviously, for a two layered earth  $N_0$  and  $K_0$  as found in (8) and (9) can be approximated by

$$K_0 \approx \gamma_0 / n_1^2$$

$$N_0 \approx \gamma_0$$

for those values of  $\alpha$  where

$$\alpha \geq \max(6/H_1, 10|n_1|)$$

Thus the leading terms of  $F_\ell(\alpha)$  ( $\ell = 1, 2, 3$ ) as given in (29) will behave as

$$F_{\ell q} = B_{\ell} \gamma_o^{-1} \quad \ell = 1, 2$$

$$F_{3q} = B_3 \gamma_o^{-2}$$

where  $B_1 = 2n_1^2/(n_1^2 + 1)$ ,  $B_2 = 1$  and  $B_3 = (n_1^2 - 1)/(n_1^2 + 1)$ .

The subscript  $q$  refers to quasi-static.

We can now add and subtract these terms to the original integrals given in (27) and (28) and write the Sommerfeld integrals as follows

$$V_{\ell} = V_{\ell}^{(1)} + V_{\ell}^{(2)} + \Delta V_{\ell} \quad (50)$$

where

$$\begin{aligned} V_{\ell}^{(1)} &= B_{\ell} \int_0^{\infty} e^{-\gamma_o b} J_o(\alpha \rho) \alpha \gamma_o^{-1} d\alpha \\ V_{\ell}^{(2)} &= \int_{\alpha_o}^{\infty} [F_{\ell}(\alpha) - F_{\ell q}(\alpha)] e^{-\gamma_o b} J_o(\alpha \rho) \alpha d\alpha \\ \text{and } \Delta V_{\ell} &= \int_0^{\alpha_o} [F_{\ell}(\alpha) - F_{\ell q}(\alpha)] e^{-\gamma_o b} J_o(\alpha \rho) \alpha d\alpha \end{aligned} \quad (51)$$

where  $\alpha_o = \max(6/H_1, 10|n_1|)$ ,  $b = Z + H_o$  and  $\ell = 1$  or  $2$ .

The leading integral  $V_{\ell}^{(1)}$  is known explicitly from (24) in terms of  $G_{12}$  as

$$V_{\ell}^{(1)} = B_{\ell} \frac{e^{iR}}{R} \quad (52)$$

The integral  $\Delta V_{\ell}$ , integrating from  $0$  to  $\alpha_o$  still needs to be evaluated numerically in the usual manner. However, the remaining integral  $V_{\ell}^{(2)}$  can be obtained analytically since now the integrand converges rapidly as  $F_{\ell}(\alpha)$  approaches  $F_{\ell q}(\alpha)$  for large  $\alpha$ . This integral is evaluated in Appendix A with the result given as

$$V_{\ell}^{(2)} = C_{\ell} \{ b \ln(R+b) - R + [\gamma + \ln(\alpha_o/2)]b + e^{-\alpha_o b} / \alpha_o \} \quad \ell = 1, 2 \quad (53)$$

where  $C_1 = 2n_1^2/(n_1^2 + 1)$ ,  $C_2 = (n_1^2 - 1)/4$  and  $\gamma = .57721566$  is Euler's constant.

Similarly, we can split up the expression for  $V_3$  given in (28) in the following form

$$V_3 = V_3^{(1)} + V_3^{(2)} + V_3^{(3)} + \Delta V_3 \quad (54)$$

where

$$\begin{aligned} V_3^{(1)} &= B_3 \cos \theta \frac{\partial}{\partial \rho} \int_b^\infty db \int_0^\infty e^{-\gamma_0 b} J_0(\alpha \rho) \alpha \gamma_0^{-1} d\alpha \\ V_3^{(2)} &= B_3 \cos \theta \frac{\partial}{\partial \rho} \int_{\alpha_0}^\infty \left[ \frac{1}{\gamma_1^2} - \frac{1}{\gamma_0^2} \right] e^{-\gamma_0 b} J_0(\alpha \rho) \alpha d\alpha \\ V_3^{(3)} &= B_3 \cos \theta \frac{\partial}{\partial \rho} \int_{\alpha_0}^\infty [F_3(\alpha) - B_3 \gamma_1^{-2}] e^{-\gamma_0 b} J_0(\alpha \rho) \alpha d\alpha \end{aligned}$$

and finally

$$\Delta V_3 = B_3 \cos \theta \frac{\partial}{\partial \rho} \int_0^{\alpha_0} [F_3(\alpha) - B_3 \gamma_1^{-2}] e^{-\gamma_0 b} J_0(\alpha \rho) \alpha d\alpha \quad (55)$$

We note that in (54) an additional term  $B_3 \gamma_1^{-2}$  has been added and subtracted instead of just adding and subtracting  $B_3 \gamma_0^{-2}$ . The reason for this kind of arrangement is to avoid the singularity at  $\alpha = 1$  when we integrate numerically from 0 to  $\alpha_0$  along the real axis in the complex  $\alpha$ -plane.

On the other hand, in the analytical evaluation of  $V_3^{(2)}$ , the path of integration is to be understood as being indented into the lower half plane around the branch point at  $\alpha = 1$ .

A similar technique as applied to  $V^{(2)}$  can be applied to the different terms of  $V_3$ . Analytical expression for  $V_3^{(1)}$  is derived in Appendix B as

$$V_3^{(1)} = -B_3 \rho \cos \theta \{ [R(R+b)]^{-1} - (.5) \ln(R+b) - \frac{1}{2}(\gamma - \frac{1}{2} - \pi i/2 - \ln 2) \} \quad (56)$$

Thus, the leading term of  $V_3$  behaves as  $1/R$ , which is similar to the leading terms of  $V_1$  and  $V_2$ . On the other hand, analytical expressions for  $V_3^{(2)}$  and  $V_3^{(3)}$  are known as (Appendix B).

$$V_3^{(2)} = \frac{(n_1^2 - 1)}{2} B_3 \rho \cos \theta [b(R+b)^{-1} + (\gamma - \frac{1}{2} - \pi i/2 - \ln 2 + \frac{n_1^2}{(n_1^2 - 1)} \ln n_1) + \ln(R+b)] \quad (57)$$

and

$$V_3^{(3)} = -C_3 \rho \cos \phi [\ln(b+R) + b(R-b)^{-1} + (\gamma - \frac{1}{2} - \ln 2 + \ln \alpha_0)] \quad (58)$$

where  $C_3 = (3n_1^2 + 1)(n_1^2 - 1)^2(n_1^2 + 1)^{-2}/8$  and  $\gamma$  is Euler's constant. The last term  $\Delta V_3$  will be evaluated numerically. We note that, once all the  $V$ 's are found and then substitute in (25) and (26), expressions for the field components are then carried out analytically according to (29a).

## 5. Discussion of results

A computer program was developed for the computation of the frequency-domain electromagnetic response of an electric dipole located above a two-layer earth representing a non-reinforced concrete slab on the surface of a dissipative earth. The program computes all three components of the electric and magnetic field simultaneously for an arbitrary-oriented dipole with a known dipole moment. Unless otherwise specified, the dipole source is assumed to be always located along the vertical axis at a given height  $h_0$ . Geometry indicating relative positions of the source and observation points is shown in Figure 5. Also, relevant parameters for the computations in this section are chosen as follows:

Frequency of operation = 300 MHz

Relative dielectric constant and conductivity in

- 1) Air,  $(\epsilon_{r0}, \sigma_0) = (1.0, 0.00)$
- 2) Cement slab,  $(\epsilon_{r1}, \sigma_1) = (3.0, 0.002)$
- 3) Earth,  $(\epsilon_{r2}, \sigma_2) = (10.0, 0.01)$

Slab width  $h_1 = .1 \text{ m}$

In order to check the numerical accuracy of the program, we have first computed the vertical electric field component due to a vertical dipole above a homogenous dissipative earth, for which the analytical solution as well as the numerical solution is available [Chang and Wait, 1970]. Accuracy to within five digits is achieved for any given distance.

Next, asymptotic expansion of the exact Sommerfeld integrals for high-angle observations is used to compare with results obtained numerically for the case when the observation point is located on the slab surface at a fixed observation angle  $\theta = 5^\circ$ . We vary the separation between the source and the

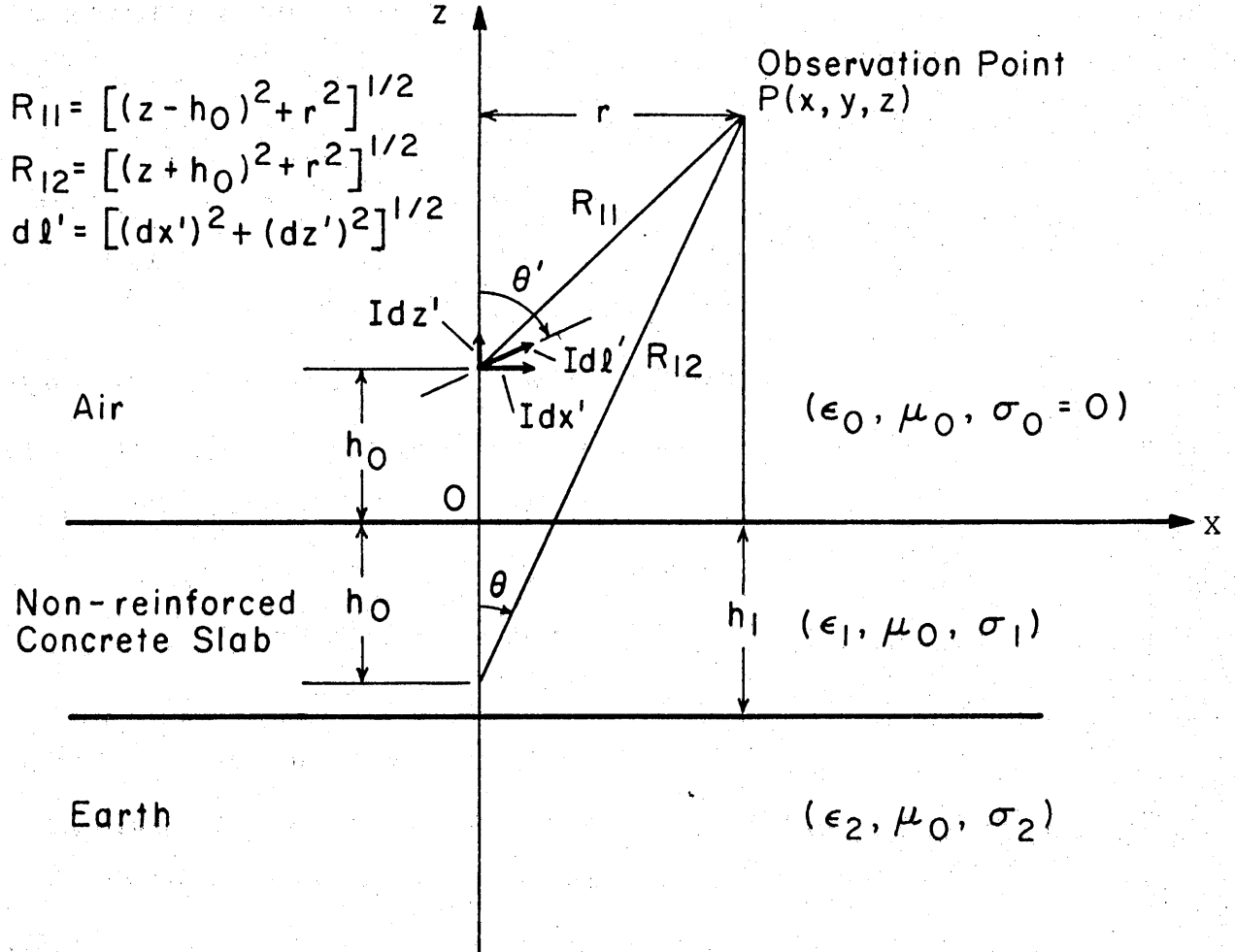


Fig. 5: A tilted dipole above a two layer half-space.

observation point and the result is shown in Table 4-9 together with the sky-wave (plane wave) solution for three different orientations of sources, a vertical dipole (Case I); and a horizontal dipole observed in the plane of the dipole (Case II); and a horizontal dipole observed in the plane perpendicular to the dipole (Case III). Our results from the exact evaluation of the Sommerfeld integrals are all within a fraction of a percent for distances about 5 meters or larger (in this case, a free-space wavelength is one meter). Only when the distance drops to within one meter does the two results show any significant difference.

Comparison is also made for a fixed observation distance  $R = 40$  meters, ( $R = R_{12}$ ), and a varying observation angle ranging from  $5^\circ$  to  $80^\circ$  (Table 10-12).

The agreement is again excellent until the observation angle is near grazing (i.e. the case when  $\theta = 80^\circ$ ). This is obviously due to the limitation of the sky-wave solution near the slab surface.

The electromagnetic field components as obtained by a two-term asymptotic expansion with the inclusion of the contribution from the ground wave correction (see Section 4.1) are tabulated in Table 13 for angles  $\theta = 30^\circ$ ,  $45^\circ$  and  $80^\circ$  and  $R = 40$  meters. Clearly, these results with ground wave corrections are now in good agreement with the exact numerical results given in Table 10-12. We note however that computation time for the asymptotic result is much less than the time spent in evaluating the exact Sommerfeld integrals.

Comparison of the quasi-static and exact results is shown in Table 14 for  $R = .005$  meters and  $\theta = 4.5^\circ$ . As a rule of thumb, the time consumed in computing the quasi-static result is less than one third the time spent in getting the exact answer.

TABLE 4

FREQUENCY= 3.00E+08 C/S  
 REFRACTIVE INDICES OF AIR, CEMENT AND EARTH RESPECTIVELY  
 NU= 1.0000+J 0.0000 EPSR0= 1.0E+00 SIGMA0= 0.  
 N1= 1.7324+J .0346 EPSR1= 3.0E+00 SIGMA1= 2.000E-03  
 N2= 3.1637+J .0947 EPSR2= 1.0E+01 SIGMA2= 1.000E-02  
 Z= 0. M OBSERVATION HEIGHT  
 MU= 3.465E+01 M DIPOLE HEIGHT  
 MI= 1.000E-01 M SLAB WIDTH  
 M= 4.000E+01 M SOURCE TO OBSERVATION DISTANCE  
 THETA= 5.0 DEG ANGLE OF INCIDENCE

|          | PLANE WAVE SOLUTION          | EXACT DIPOLE SOLUTION        | DIFFERENCE                   | RELATIVE DIF |
|----------|------------------------------|------------------------------|------------------------------|--------------|
| Case I   |                              |                              |                              |              |
|          | PARALLEL POLARIZATION        | VERTICAL DIPOLE              |                              |              |
| EX=      | 3.056898E-02+J 3.703096E-01  | 3.097773E-02+J 3.703326E-01  | 4.087484E-04+J 2.304060E-05  | 1.10164E-03  |
| EZ=      | 2.400224E-02+J 5.427249E-02  | 2.394655E-02+J 5.430786E-02  | -5.568761E-05+J 3.536882E-05 | 1.11149E-03  |
| HY=      | 4.743142E-04+J-1.160146E-03  | 4.754081E-04+J-1.160098E-03  | 1.093875E-06+J 4.805487E-08  | 8.73337E-04  |
| Case II  |                              |                              |                              |              |
|          | PARALLEL POLARIZATION        | HORIZONTAL DIPOLE            |                              |              |
| EX=      | 3.832980E-01+J 4.229588E+00  | 3.802394E-01+J 4.227314E+00  | -3.058576E-03+J-2.274445E-03 | 8.98025E-04  |
| EZ=      | -1.614701E-01+J 4.339812E-01 | -1.818789E-01+J 4.339581E-01 | -4.087472E-04+J-2.309396E-05 | 8.70079E-04  |
| HY=      | 5.421436E-03+J-1.326053E-02  | 5.413494E-03+J-1.326665E-02  | -7.942327E-06+J-6.123130E-06 | 6.99900E-04  |
| Case III |                              |                              |                              |              |
|          | PERPENDICULAR POLARIZATION   | HORIZONTAL DIPOLE            |                              |              |
| EX=      | 3.407456E-01+J 4.251730E+00  | 3.876014E-01+J 4.249454E+00  | -3.143746E-03+J-2.276102E-03 | 9.09567E-04  |
| EY=      | 5.434058E-03+J-1.528765E-02  | 5.426073E-03+J-1.329364E-02  | -7.985183E-06+J-5.987529E-06 | 6.95111E-04  |
| EZ=      | -9.039669E-05+J-9.836337E-04 | -8.650202E-05+J-9.814461E-04 | 3.896664E-06+J 2.187586E-06  | 4.53562E-03  |



TABLE 5

FREQ= 3.0E+08 C/S  
 REFRACTIVE INDICES OF AIR-Glass AND FATH RESPECTIVELY  
 N1= 1.0000+J 0.0000 EPSR0= 1.0E+00 SIGMA0= 0.  
 N2= 1.7324+J 0.0440 EPSR1= 3.0E+00 SIGMA1= 2.000E-03  
 N3= 1.637+J 0.047 EPSR2= 1.0E+01 SIGMA2= 1.000E-02  
 Z= 0. OBSERVATION HEIGHT  
 H= 1.000E+01 M DIPOLE HEIGHT  
 W= 1.000E+01 M SLIT WIDTH  
 D= 2.000E+01 M SOURCE TO OBSERVATION DISTANCE  
 THETA= 5.0 DEG ANGLE OF INCIDENCE

|          | PLANE WAVE SOLUTION          | EXACT DIPOLE SOLUTION        | DIFFERENCE                   | RELATIVE DIF. |
|----------|------------------------------|------------------------------|------------------------------|---------------|
| Case I   | PARALLEL POLARIZATION        | VERTICAL DIPOLE              |                              |               |
| EX=      | 1.163509E-01+J 1.340270E-01  | 1.180111E-01+J 7.339473E-01  | 1.660219E-03+J-7.962892E-05  | 2.23592E-03   |
| EZ=      | 1.383776E-01+J 1.293066E-01  | 1.381797E-01+J 1.302282E-01  | -1.978884E-04+J 3.215362E-04 | 1.98841E-03   |
| HY=      | 7.635151E-04+J-2.394850E-03  | 7.579462E-04+J-2.391171E-03  | 4.431073E-06+J-3.203410E-07  | 1.77109E-03   |
| Case II  | PARALLEL POLARIZATION        | HORIZONTAL DIPOLE            |                              |               |
| EX=      | 1.403992E+00+J 8.356519E+00  | 1.451100E+00+J 8.358589E+00  | -1.289184E-02+J-7.929718E-03 | 1.78407E-03   |
| EZ=      | -2.970482E-01+J 8.927332E-01 | -2.987085E-01+J 8.928127E-01 | -1.660277E-03+J 7.950281E-05 | 1.76554E-03   |
| HY=      | 8.612717E-03+J-2.732754E-02  | 8.579327E-03+J-2.734948E-02  | -3.336990E-05+J-2.193192E-05 | 1.39371E-03   |
| Case III | PERPENDICULAR POLARIZATION   | HORIZONTAL DIPOLE            |                              |               |
| EX=      | 1.448149E+00+J 8.400950E+00  | 1.448764E+00+J 8.401593E+00  | -1.322477E-02+J-7.914995E-03 | 1.60705E-03   |
| EY=      | 8.633339E-03+J-2.733359E-02  | 8.599879E-03+J-2.740508E-02  | -3.351055E-05+J-2.139408E-05 | 1.38418E-03   |
| EZ=      | -3.428734E-04+J-1.175624E-03 | -3.266890E-04+J-1.938306E-03 | 1.618485E-05+J 7.317845E-06  | 9.03639E-03   |

TABLE 6

```

EARTHQUAKE= 1.000E+00 C/A
RESPECTIVE VALUES OF DISPLACEMENT AND EARTH RESPECTIVELY
R1= 1.600E+00 J 0.0000
R2= 1.732E+00 J 0.0340
R3= 3.1637E+00 J 0.0947
Z= 0.0 OBSERVATION HEIGHT
R1= 0.042E+00 M DIPOLE HEIGHT
R2= 1.000E+01 M SLASH WIDTH
R3= 1.000E+01 M SLASH OF OBSERVATION DISTANCE
R4= 5.0 DEG ANGLE OF INCIDENCE

```

|                 | PLANE WAVE SOLUTION          | EXACT DIPOLE SOLUTION        | DIFFERENCE                   | RELATIVE DIFF. |
|-----------------|------------------------------|------------------------------|------------------------------|----------------|
| <b>Case I</b>   |                              |                              |                              |                |
|                 | PARALLEL POLARIZATION        | VERTICAL DIPOLE              |                              |                |
| EX=             | 2.613969E-01+J 1.663447E+00  | 2.682098E-01+J 1.462810E+00  | 6.812942E-03+J-8.369559E-04  | 4.61551E-03    |
| EZ=             | 6.115241E-01+J 3.410448E-01  | 6.150482E-01+J 3.436857E-01  | -4.759392E-04+J 2.640938E-03 | 3.80874E-03    |
| HY=             | 1.336417E-03+J-4.832545E-03  | 1.354862E-03+J-4.835663E-03  | 1.804430E-05+J-3.118158E-06  | 3.64639E-03    |
| <b>Case II</b>  |                              |                              |                              |                |
|                 | PARALLEL POLARIZATION        | HORIZONTAL DIPOLE            |                              |                |
| EX=             | 3.520552E+00+J 1.661682E+01  | 3.468997E+00+J 1.658793E+01  | -5.215500E-02+J-2.889139E-02 | 3.51825E-03    |
| EZ=             | -5.592796E-01+J 1.797233E+00 | -5.660924E-01+J 1.798075E+00 | -6.812839E-03+J 8.366830E-04 | 3.64123E-03    |
| HY=             | 1.527933E-02+J-5.523624E-02  | 1.514558E-02+J-5.532048E-02  | -1.343162E-04+J-8.424614E-05 | 2.76431E-03    |
| <b>Case III</b> |                              |                              |                              |                |
|                 | PERPENDICULAR POLARIZATION   | HORIZONTAL DIPOLE            |                              |                |
| EX=             | 3.507541E+00+J 1.570199E+01  | 3.504112E+00+J 1.667305E+01  | -5.342914E-02+J-2.884014E-02 | 3.56371E-03    |
| HY=             | 1.531724E-02+J-5.534493E-02  | 1.518255E-02+J-5.543214E-02  | -1.346855E-04+J-8.220927E-05 | 2.74547E-03    |
| EZ=             | -4.232444E-04+J-3.494878E-03 | -7.581100E-04+J-3.838788E-03 | 6.513434E-05+J 2.609076E-05  | 1.79317E-02    |

TABLE 7

```

ELEVATION= 1.000E+00
PERSPECTIVE IMAGES OF 1-CURRENT AND EARTH RESPECTIVELY
M1= 1.0000E+00 EPSR0= 1.0E+00 SIGMA0= 0.
N1= 1.7500E+01 EPSR1= 3.0E+00 SIGMA1= 2.000E-03
N2= 3.1637E+01 EPSR2= 1.0E+01 SIGMA2= 1.000E-02

Z= 0. OBSERVATION HEIGHT
M0= 4.000E+00 DIRECTION
M1= 1.000E+01 SLAR WIDTH
M2= 5.000E+01 SOURCE OF INCIDENCE
THETA= 5.0 DEG ANGLE OF INCIDENCE

```

|                 | PLANE WAVE SOLUTION          | EXACT DIPOLE SOLUTION        | DIFFERENCE                   | RELATIVE DIFF. |
|-----------------|------------------------------|------------------------------|------------------------------|----------------|
| <b>Case I</b>   |                              |                              |                              |                |
|                 | PARALLEL POLARIZATION        | VERTICAL DIPOLE              |                              |                |
| EX=             | 4.499625E+01*J 2.4943260E+00 | 4.758635E+01*J 2.937652E+00  | 2.890104E-02*J-5.608306E-03  | 9.89271E-03    |
| EY=             | 2.556913E+00*J 1.032220E+00  | 2.559207E+00*J 1.053921E+00  | 2.292235E-03*J 2.166115E-02  | 7.87004E-03    |
| EZ=             | 2.614555E+03*J-2.998497E-03  | 2.693199E+03*J-8.706489E-03  | 7.484266E-05*J-2.239259E-05  | 7.73629E-03    |
| <b>Case II</b>  |                              |                              |                              |                |
|                 | PARALLEL POLARIZATION        | HORIZONTAL DIPOLE            |                              |                |
| EX=             | 7.294091E+00*J 3.317812E+01  | 7.033542E+00*J 3.307163E+01  | -2.045090E-01*J-1.064897E-01 | 6.81941E-03    |
| EY=             | -1.213090E+00*J 3.508423E+00 | -1.241947E+00*J 3.573827E+00 | -2.890096E-02*J 5.603890E-03 | 7.76098E-03    |
| EZ=             | 2.992023E+02*J-1.106897E-01  | 2.940824E+02*J-1.110340E-01  | -5.219685E-04*J-3.442664E-04 | 5.44369E-03    |
| <b>Case III</b> |                              |                              |                              |                |
|                 | PERPENDICULAR POLARIZATION   | HORIZONTAL DIPOLE            |                              |                |
| EX=             | 7.304447E+00*J 3.434953E+01  | 7.095719E+00*J 3.324287E+01  | -2.091677E-01*J-1.066518E-01 | 6.90723E-03    |
| EY=             | 3.609333E-02*J-1.109170E-01  | 2.948051E-02*J-1.112547E-01  | -5.231212E-04*J-3.371142E-04 | 5.40718E-03    |
| EZ=             | -1.621910E-03*J-7.723011E-03 | -1.435503E-03*J-7.626778E-03 | 2.564072E-04*J 9.623244E-05  | 3.52895E-02    |

TABLE 8

PROBLEMS= 3.00E+00 F/Z  
 REFRACTIVE INDICES OF AIR, GLASS, AND FATH RESPECTIVELY  
 N1= 1.0000E+00 0.0001 EPS0= 1.0E+00 SIGMA0= 0.  
 N2= 1.5172E+01 0.0340 EPS1= 3.0E+00 SIGMA1= 2.000E-03  
 N3= 3.1537E+01 0.0547 EPS2= 1.0E+01 SIGMA2= 1.000E-02  
 Z= 0.0 M OBSERVATION HEIGHT  
 H1= 1.000E+00 M DIPOLE HEIGHT  
 H2= 1.000E+00 M SLASH WIDTH  
 W= 2.000E+00 M SOURCE TO OBSERVATION DISTANCE  
 THETA= 5.6 DEG ANGLE OF INCIDENCE

|                 | PLANE WAVE SOLUTION                                       | EXACT DIPOLE SOLUTION                            | DIFFERENCE                   | RELATIVE DIF. |
|-----------------|---|--|------------------------------|---------------|
| <b>Case I</b>   |   |  |                              |               |
| EX=             | PARALLEL POLARIZATION<br>1.545409E-01+J 7.501099E+00      | VERTICAL DIPOLE<br>3.753434E-01+J 7.440945E+00   | 2.208026E-01+J-6.015405E-02  | 3.07164E-02   |
| FZ=             | 1.415506E+00+J 5.831475E+00                               | 1.632323E+01+J 6.192073E+00                      | 1.681721E-01+J 3.605977E-01  | 2.27907E-02   |
| MY=             | 7.394143E-03+J-2.403323E-02                               | 7.903052E-03+J-2.432010E-02                      | 5.049086E-04+J-2.868624E-04  | 2.27088E-02   |
| <b>Case II</b>  |   |  |                              |               |
| EX=             | PARALLEL POLARIZATION<br>1.520141E+01+J 6.329597E+01      | HORIZONTAL DIPOLE<br>1.406266E+01+J 8.273756E+01 | -1.139155E+00+J-5.584101E-01 | 1.51167E-02   |
| FZ=             | -4.194126E+00+J 8.520024E+00                              | -4.416924E+00+J 8.580113E+00                     | -2.208026E-01+J 6.008417E-02 | 2.37102E-02   |
| MY=             | 6.446116E-02+J-2.147011E-01                               | 8.146476E-02+J-2.771462E-01                      | -2.896399E-03+J-2.445124E-03 | 1.31191E-02   |
| <b>Case III</b> |   |  |                              |               |
| EX=             | PERPENDICULAR POLARIZATION<br>1.524195E+01+J 9.374011E+01 | HORIZONTAL DIPOLE<br>1.413194E+01+J 8.317381E+01 | -1.160016E+00+J-5.663007E-01 | 1.53038E-02   |
| MY=             | 4.476476E-02+J-2.152657E-01                               | 6.183386E-02+J-2.776816E-01                      | -2.900905E-03+J-2.415911E-03 | 1.30404E-02   |
| MZ=             | -3.500897E-03+J-1.949366E-02                              | -2.067248E-03+J-1.895070E-02                     | 1.502644E-03+J 5.429010E-04  | 8.38119E-02   |

TABLE 9

FOR POLARIZATION OF THE REFLECTED AND TRANSMITTED WAVES RESPECTIVELY  
 REFLECTIVE COEFFICIENTS OF THE REFLECTED AND TRANSMITTED WAVES  
 R1= 1.0000000000000000 EPSR0= 1.0E+00 SIGMA0= 0.  
 R2= 1.7320508075688772 EPSR1= 3.0E+00 SIGMA1= 2.000E-03  
 R3= 3.162277660168379 EPSR2= 1.0E+01 SIGMA2= 1.000E-02  
 Z= 0.0000000000000000 OBSERVATION HEIGHT  
 P= 0.0000000000000000 DIPOLE POSITION  
 M= 1.0000000000000000 SLANT VOLUME  
 R= 1.0000000000000000 SOURCE TO OBSERVATION DISTANCE  
 THETA= 45.0 DEG ANGLE OF INCIDENCE

| PLANE WAVE SOLUTION |                              | EXACT DIPOLE SOLUTION        |                              | DIFFERENCE  |  | RELATIVE DIF. |  |
|---------------------|------------------------------|------------------------------|------------------------------|-------------|--|---------------|--|
| Case I              |                              | VERTICAL DIPOLE              |                              |             |  |               |  |
| EX=                 | -3.26944E+00+J 1.510750E+01  | -2.054056E+00+J 1.480040E+01 | 1.215412E+00+J-3.070962E-01  | 8.38968E-02 |  |               |  |
| EZ=                 | 6.341610E+03+J 2.673160E+01  | 6.635744E+01+J 2.977550E+01  | 2.441340E+00+J 3.043903E+00  | 5.36491E-02 |  |               |  |
| HY=                 | 1.844224E-02+J-4.727991E-02  | 2.063998E-02+J-4.916431E-02  | 2.157301E-03+J-1.884407E-03  | 5.37204E-02 |  |               |  |
| Case II             |                              | HORIZONTAL DIPOLE            |                              |             |  |               |  |
| EX=                 | 1.745629E+01+J 1.668591E+02  | 1.408939E+01+J 1.653235E+02  | -3.366904E+00+J-1.535627E+00 | 2.23030E-02 |  |               |  |
| EZ=                 | -1.247930E+01+J 1.507274E+01 | -1.369472E+01+J 1.537938E+01 | -1.215412E+00+J 3.066417E-01 | 6.08701E-02 |  |               |  |
| HY=                 | 2.112570E-01+J-5.404118E-01  | 2.019166E-01+J-5.521007E-01  | -9.341354E-03+J-1.168890E-02 | 2.54531E-02 |  |               |  |
| Case III            |                              | PERPENDICULAR POLARIZATION   |                              |             |  |               |  |
| EX=                 | 1.745629E+01+J 1.668591E+02  | 1.305721E+01+J 1.461773E+02  | -3.396959E+00+J-1.596273E+00 | 2.25070E-02 |  |               |  |
| EZ=                 | 2.117521E-01+J-5.415160E-01  | 2.024030E-01+J-5.531612E-01  | -9.34136E-03+J-1.164324E-02  | 2.53506E-02 |  |               |  |
| HY=                 | -4.274396E-03+J-3.77823E-02  | 1.152342E-03+J-3.781872E-02  | 5.4428737E-03+J 1.959513E-03 | 1.52540E-01 |  |               |  |

TABLE 10

EPSR2= 3.00E-03 C/A  
 DIFFERENTIAL LOSS OF INCIDENT AND EARTH REFLECTED  
 E1= 1.0000E+01 0.0000 EPSR0= 1.0E+00 SIGMA0= 0.  
 E2= 1.7324E+01 -0.346 EPSR1= 3.0E+00 SIGMA1= 2.000E-03  
 E3= 3.1417E+01 0.947 EPSR2= 1.0E+01 SIGMA2= 1.000E-02  
 Z= 0.  
 H0= 3.444E+01 M DIPOLE HEIGHT  
 H1= 1.000E+01 M SLAB WIDTH  
 F= 4.000E+01 M SOURCE TO OBSERVATION DISTANCE  
 THETA= 30.0 DEG. ANGLE OF INCIDENCE

| PLANE WAVE SOLUTION        |                              | EXACT DIPOLE SOLUTION |                              | DIFFERENCE                   | RELATIVE DIF. |
|----------------------------|------------------------------|-----------------------|------------------------------|------------------------------|---------------|
| Case I                     |                              |                       |                              |                              |               |
| PARALLEL POLARIZATION      |                              | VERTICAL DIPOLE       |                              |                              |               |
| E <sub>X</sub> =           | 1.437133E-01+J 1.893794E+00  |                       | 1.474782E-01+J 1.894765E+00  | 3.764936E-03+J 9.676882E-04  | 2.04542E-03   |
| E <sub>Z</sub> =           | -4.784405E-01+J 1.238629E+00 |                       | -4.819455E-01+J 1.237909E+00 | -3.484980E-03+J-7.194992E-04 | 2.67874E-03   |
| H <sub>Y</sub> =           | 2.494425E-03+J-6.511404E-03  |                       | 2.708718E-03+J-6.508282E-03  | 1.329223E-05+J 3.125719E-06  | 1.93700E-03   |
| Case II                    |                              |                       |                              |                              |               |
| PARALLEL POLARIZATION      |                              | HORIZONTAL DIPOLE     |                              |                              |               |
| E <sub>X</sub> =           | 2.436754E-01+J 3.277238E+00  |                       | 2.705649E-01+J 3.275409E+00  | -4.110745E-03+J-1.829204E-03 | 1.36870E-03   |
| E <sub>Z</sub> =           | -8.262937E-01+J 2.117395E+00 |                       | -9.000509E-01+J 2.116427E+00 | -3.765250E-03+J-9.678909E-04 | 1.69039E-03   |
| H <sub>Y</sub> =           | 4.468611E-03+J-1.127409E-02  |                       | 4.664216E-03+J-1.128116E-02  | -4.397804E-06+J-3.073895E-06 | 4.39537E-04   |
| Case III                   |                              |                       |                              |                              |               |
| PERPENDICULAR POLARIZATION |                              | HORIZONTAL DIPOLE     |                              |                              |               |
| E <sub>X</sub> =           | 5.334945E-01+J 3.443960E+00  |                       | 5.323133E-01+J 3.443285E+00  | -5.705211E-03+J-6.750020E-04 | 1.46378E-03   |
| H <sub>Y</sub> =           | 5.052744E-03+J-1.225494E-02  |                       | 5.060208E-03+J-1.225636E-02  | -2.535812E-06+J 2.548874E-06 | 2.71151E-04   |
| H <sub>Z</sub> =           | -7.141734E-04+J-5.234484E-03 |                       | -6.879130E-04+J-5.226215E-03 | 2.626040E-05+J 8.272265E-06  | 5.22310E-03   |

TABLE 11

|  |                               |        |                                |                   |                               |            |  |               |  |
|--|-------------------------------|--------|--------------------------------|-------------------|-------------------------------|------------|--|---------------|--|
| FREQUENCY= 7.35 MHz CAS                                  |                               |        |                                |                   |                               |            |  |               |  |
| OBSERVATIVE POINTS OF ARRANGEMENT AND EARTH RESPECTIVELY |                               |        |                                |                   |                               |            |  |               |  |
| R0=  | 1.6000E+01                    | 3.0000 | EPS00= 1.0E+00                 | SIGMA0= 0.        |                               |            |  |               |  |
| R1=  | 1.7328E+01                    | 0.0300 | EPS01= 3.0E+00                 | SIGMA1= 2.000E-03 |                               |            |  |               |  |
| R2=  | 3.1437E+01                    | 0.0467 | EPS02= 1.0E+01                 | SIGMA2= 1.000E-02 |                               |            |  |               |  |
| Z= 0.0000E+00 OBSERVATION HEIGHT                         |                               |        |                                |                   |                               |            |  |               |  |
| H0=  | 2.0000E+01                    | M      | DIPOLE HEIGHT                  |                   |                               |            |  |               |  |
| H1=  | 1.0000E+01                    | M      | SOURCE PLANE                   |                   |                               |            |  |               |  |
| R=   | 4.0000E+01                    | M      | SOURCE TO OBSERVATION DISTANCE |                   |                               |            |  |               |  |
| THETA=   | 45.0                          | DEG    | ANGLE OF INCIDENCE             |                   |                               |            |  |               |  |
| PLANE WAVE SOLUTION                                      |                               |        | EXACT DIPOLE SOLUTION          |                   |                               | DIFFERENCE |  | RELATIVE DIF. |  |
| Case I PARALLEL POLARIZATION                             |                               |        |                                |                   |                               |            |  |               |  |
| VERTICAL DIPOLE  |                               |        |                                |                   |                               |            |  |               |  |
| FX=  | 1.744091E-01+J 2.307705E+00   |        | 1.404201E-01+J 2.309452E+00    |                   | 6.010956E-03+J 1.747347E-03   |            |  | 2.70551E-03   |  |
| EZ=  | -9.663265E-01+J 2.339485E+00  |        | -9.780035E-01+J 2.336757E+00   |                   | -1.167698E-02+J -2.928311E-03 |            |  | 4.75238E-03   |  |
| HY=  | 3.697138E-03+J -8.753624E-03  |        | 3.730370E-03+J -8.744980E-03   |                   | 3.323201E-05+J 8.643801E-06   |            |  | 3.61170E-03   |  |
| Case II PARALLEL POLARIZATION                            |                               |        |                                |                   |                               |            |  |               |  |
| HORIZONTAL DIPOLE  |                               |        |                                |                   |                               |            |  |               |  |
| FX=  | 1.713933E-01+J 2.305275E+00   |        | 1.625238E-01+J 2.302604E+00    |                   | -8.56948E-03+J -2.671583E-03  |            |  | 3.88864E-03   |  |
| EZ=  | -1.003414E+00+J 2.324021E+00  |        | -1.009424E+00+J 2.322275E+00   |                   | -6.010266E-03+J -1.745754E-03 |            |  | 2.47166E-03   |  |
| HY=  | 3.697132E-03+J -8.753624E-03  |        | 3.692385E-03+J -8.755548E-03   |                   | -4.753482E-06+J -1.924376E-06 |            |  | 5.39685E-04   |  |
| Case III PERPENDICULAR POLARIZATION                      |                               |        |                                |                   |                               |            |  |               |  |
| HORIZONTAL DIPOLE  |                               |        |                                |                   |                               |            |  |               |  |
| FX=  | 6.745937E-01+J 3.473004E+00   |        | 6.607619E-01+J 3.481107E+00    |                   | -8.831798E-03+J 2.102387E-03  |            |  | 2.56099E-03   |  |
| HY=  | 4.397418E-03+J -1.089206E-02  |        | 4.400347E-03+J -1.087186E-02   |                   | 8.929281E-06+J 1.019622E-05   |            |  | 1.15536E-03   |  |
| HZ=  | -1.273699E-03+J -5.529977E-03 |        | -1.291597E-03+J -6.527462E-03  |                   | 4.210174E-05+J 2.515011E-06   |            |  | 6.34941E-03   |  |

TABLE 12

FREQUENCY= 3.00E+08 C/S  
 REFRACTIVE INDICES OF AIR, CEMENT AND EARTH RESPECTIVELY  
 N0= 1.0000+J 0.0000 EPSR0= 1.0E+00 SIGMA0= 0.  
 N1= 1.7324+J .0346 EPSR1= 3.0E+00 SIGMA1= 2.000E-03  
 N2= 3.1637+J .0947 EPSR2= 1.0E+01 SIGMA2= 1.000E-02

Z= 0. M OBSERVATION HEIGHT  
 H0= 4.946E+00 M DIPOLE HEIGHT  
 H1= 1.000E-01 M SLAR WIDTH  
 H= 4.000E+01 M SOURCE TO OBSERVATION DISTANCE  
 THETA= 80.0 DEG ANGLE OF INCIDENCE

|          | PLANE WAVE SOLUTION           | EXACT DIPOLE SOLUTION        | DIFFERENCE                   | RELATIVE DIF. |
|----------|-------------------------------|------------------------------|------------------------------|---------------|
| Case I   | PARALLEL POLARIZATION         | VERTICAL DIPOLE              |                              |               |
| EX=      | -1.017360F-01+J 1.228208E+00  | -1.270977E-01+J 1.221023E+00 | -2.536178E-02+J-7.184984E-03 | 2.14724E-02   |
| EZ=      | -1.0492006E+00+J 2.027570E+00 | -1.162065E+00+J 1.983039E+00 | -7.005891E-02+J-4.453110E-02 | 3.61174E-02   |
| HY=      | 2.944724E-03+J-5.464346E-03   | 3.116624E-03+J-5.352220E-03  | 1.719002E-04+J 1.121264E-04  | 3.31373E-02   |
| Case II  | PARALLEL POLARIZATION         | HORIZONTAL DIPOLE            |                              |               |
| EX=      | 3.020985E-02+J 2.208427E-01   | 2.117261E-03+J 2.130390E-01  | -3.709259E-02+J-7.803715E-03 | 1.77914E-01   |
| FZ=      | -1.954812E-01+J 3.559357E-01  | -1.701755E-01+J 3.629195E-01 | 2.530570E-02+J 6.983774E-03  | 6.54922E-02   |
| HY=      | 5.192342E-04+J-9.635117E-04   | 4.324112E-04+J-9.836515E-04  | -8.682303E-05+J-2.013975E-05 | 8.29486E-02   |
| Case III | PERPENDICULAR POLARIZATION    | HORIZONTAL DIPOLE            |                              |               |
| EX=      | 4.760556E-01+J 1.082661E+00   | 4.616274E-01+J 1.100541E+00  | -1.443819E-02+J 1.792027E-02 | 1.92624E-02   |
| HY=      | 9.406543E-04+J-3.176933E-03   | 1.046706E-03+J-3.784495E-03  | 6.015999E-05+J-7.562319E-06  | 1.54418E-02   |
| HZ=      | -1.2444486E-03+J-2.830190E-03 | -1.198245E-03+J-2.878164E-03 | 4.624052E-05+J-4.799345E-05  | 2.13767E-02   |



TABLE 13

## STEEPEST DESCENT RESULTS

FREQUENCY = 3.00E+08 C/S

REFRACTIVE INDICES OF AIR CEMENT AND EARTH RESPECTIVELY

N0= 1.0000+J 0.0000 EPSRO= 1.0E+00 SIGMAO= 0.

N1= 1.7324+J .0346 EPSR1= 3.0E+00 SIGMA1= 2.000E-03

N2= 3.1637+J .0947 EPSR2= 1.0E+01 SIGMA2= 1.000E-02

Z= 0. M OBSERVATION HEIGHT

H1= 1.000E-01 M SLAB WIDTH

R= 4.000E+01 M SOURCE TO OBSERVATION DISTANCE

 $\theta = 30^\circ, h_o = 34.64 \text{ m}$  $\theta = 45^\circ, h_o = 28.28 \text{ m}$  $\theta = 80^\circ, h_o = 6.946 \text{ m}$ Parallel Polarization  
Vertical Dipole

EX = 1.476711E-01+J 1.894917E+00  
 EZ = -4.813033E-01+J 1.238235E+00  
 HY = 2.708173E-03+J-6.508386E-03

1.412327E-01+J 2.309387E+00  
 -9.769887E-01+J 2.336869E+00  
 3.729027E-03+J-8.745169E-03

-1.293017E-01+J 1.219652E+00  
 -1.163315E+00+J 1.979569E+00  
 3.121152E-03+J-5.342210E-03

Parallel Polarization  
Horizontal Dipole

EX = 2.790657E-01+J 3.274560E+00  
 EZ = -8.998380E-01+J 2.116889E+00  
 HY = 4.662933E-03+J-1.128274E-02

1.619211E-01+J 2.302223E+00  
 -1.008123E+00+J 2.323156E+00  
 3.689543E-03+J-8.757071E-03

2.012439E-03+J 2.119788E-01  
 -1.692147E-01+J 3.641888E-01  
 4.332300E-04+J-9.896551E-04

Perpendicular Polarization  
Horizontal Dipole

EX = 5.322586E-01+J 3.943356E+00  
 HY = 5.059257E-03+J-1.225730E-02  
 HZ = -6.884591E-04-J-5.226918E-03

6.701051E-01+J 3.481016E+00  
 4.404040E-03+J-1.087320E-02  
 -1.233093E-03+J-6.527412E-03

4.621943E-01+J 1.101173E+00  
 1.056692E-03+J-3.786900E-03  
 -1.198232E-03+J-2.883319E-03

TABLE 14

FREQUENCY= 3.00E+08 C/S  
 REFRACTIVE INDICES OF AIR, CEMENT AND EARTH RESPECTIVELY  
 N0= 1.0000+J 0.0000 EPSR0= 1.0E+00 SIGMA0= 0.  
 N1= 1.7324+J .0346 EPSR1= 3.0E+00 SIGMA1= 2.000E-03  
 N2= 3.1637+J .0947 EPSR2= 1.0E+01 SIGMA2= 1.000E-02  
  
 Z= 0. M OBSERVATION HEIGHT  
 H0= 4.985E-03 M DIPOLE HEIGHT  
 H1= 1.000E-01 M SLAB WIDTH  
 R= 5.000E-03 M SOURCE TO OBSERVATION DISTANCE  
 THETA= 4.5 DEG ANGLE OF INCIDENCE

| QUASI-STATIC SOLUTION             |                                 | EXACT DIPOLE SOLUTION           |  |
|-----------------------------------|---------------------------------|---------------------------------|--|
| <u>Parallel Polarization</u>      |                                 | <u>Vertical Dipole</u>          |  |
| EX =                              | -1.339861E +05 +J-4.472028E +06 | -1.337351E +05 +J-4.498663E +06 |  |
| EZ =                              | -1.135130E +06 +J 1.134747E +08 | -1.134994E +06 +J 1.134375E +08 |  |
| HY =                              | 3.749333E +02 +J 3.750498E +00  | 3.747873E +02 +J 3.749815E +00  |  |
| <u>Parallel Polarization</u>      |                                 | <u>Horizontal Dipole</u>        |  |
| EX =                              | -5.590979E +05 +J-1.868388E +07 | -5.618232E +05 +J-1.867090E +07 |  |
| EZ =                              | 1.339565E +05 +J-1.343289E +07  | 1.337351E +05 +J-1.344194E +07  |  |
| HY =                              | 3.962958E +03 +J 2.035858E +01  | 3.966040E +03 +J 2.433938E +01  |  |
| <u>Perpendicular Polarization</u> |                                 | <u>Horizontal Dipole</u>        |  |
| EX =                              | -5.702029E +05 +J-1.901706E +07 | -5.722937E +05 +J-1.902040E +07 |  |
| HY =                              | 3.970331E +03 +J 2.057906E +01  | 3.973397E +03 +J 2.455947E +01  |  |
| HZ =                              | 2.499527E +02 +J 1.257811E -02  | 2.498108E +02 +J 1.093684E -02  |  |

To further demonstrate the range of validity of the approximate methods, we show in Figure 6 the magnitude of  $E_z$  on the slab surface versus the distance  $R$  ( $R=R_{12}$ ) for a fixed observation angle  $\theta = 5^\circ$ . The solid curve represents the exact field calculation for the two different orientations of the dipole source (vertical and horizontal) observed in the plane of the dipole ( $\theta = 0^\circ$ ). The long dash line represents the asymptotic results while the long dash-short dash line represents the quasi-static result. Similar comparison can be made for other components of the field.

As pointed out by Lytle, et al. [1976], a convenient way to display the electromagnetic field structure near the dipole source involves the use of the power flux or the time-average Poynting vector  $\bar{P}$  defined as  $\frac{1}{2}\text{Re}(\bar{E} \times \bar{H}^*)$ . It is well-known that in the far-zone the power flux  $\bar{P}_0$  of an isolated dipole in free space can be given as

$$\bar{P}_0 = \bar{a}_r P_0 \sin^2 \theta; \quad P_0 = \eta_0 (2\lambda R_{11})^{-2}$$

where  $\eta_0 = 120\pi$  ohm is the free-space characteristic impedance and  $\lambda$  is the free-space wavelength. Thus, the power flux density in this case points radially outward, while decaying with the rate of  $R_{11}^{-2}$ . The magnitude of the power flux on the other hand vanishes along the dipole axis at  $\theta = 0^\circ$  but is at maximum in the broadside direction, i.e.  $\theta = 90^\circ$ .

The power flux of a vertical dipole source, normalized to  $P_0$  above a two-layer earth surface is plotted in Fig. 7. It is seen that the direction of the power flux as indicated by the direction of the arrow departs significantly from the radial direction near the slab surface. Magnitude of the normalized power flux (1 cm of the thick arrow corresponds

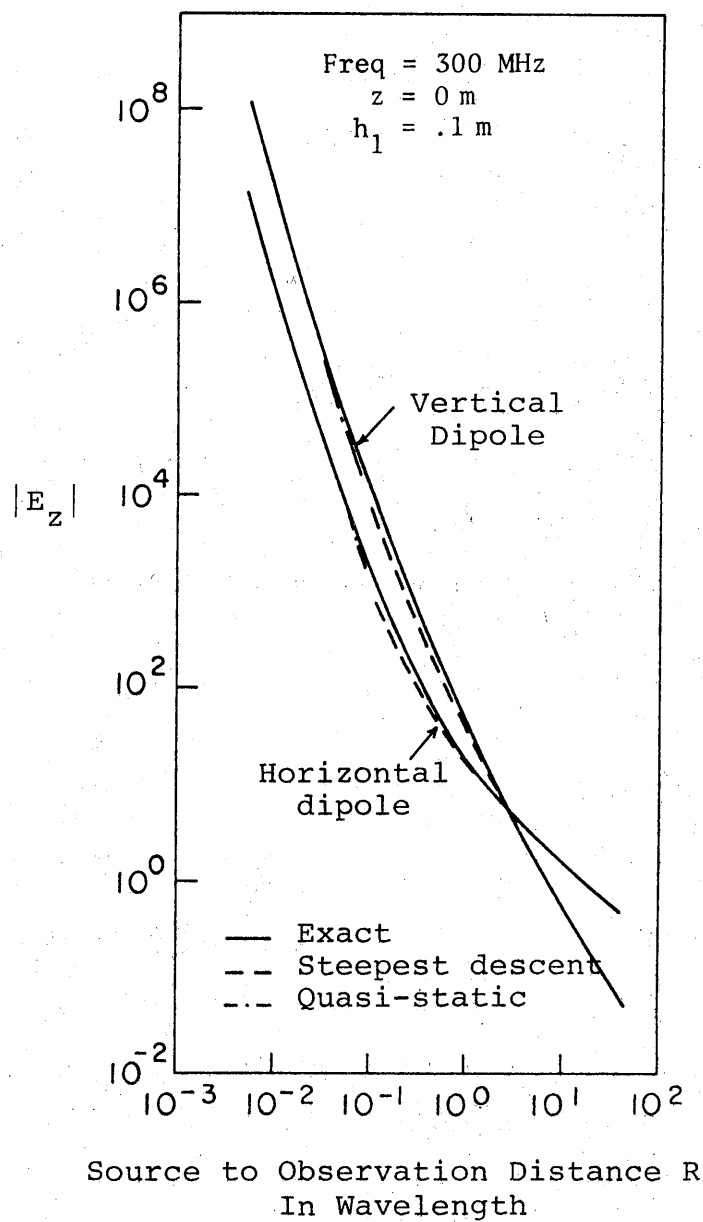


Figure 6. Magnitude of the vertical electrical field  $E_z$  on the slab surface as a function of distance  $R$  for an angle  $\theta = 5^\circ$ .

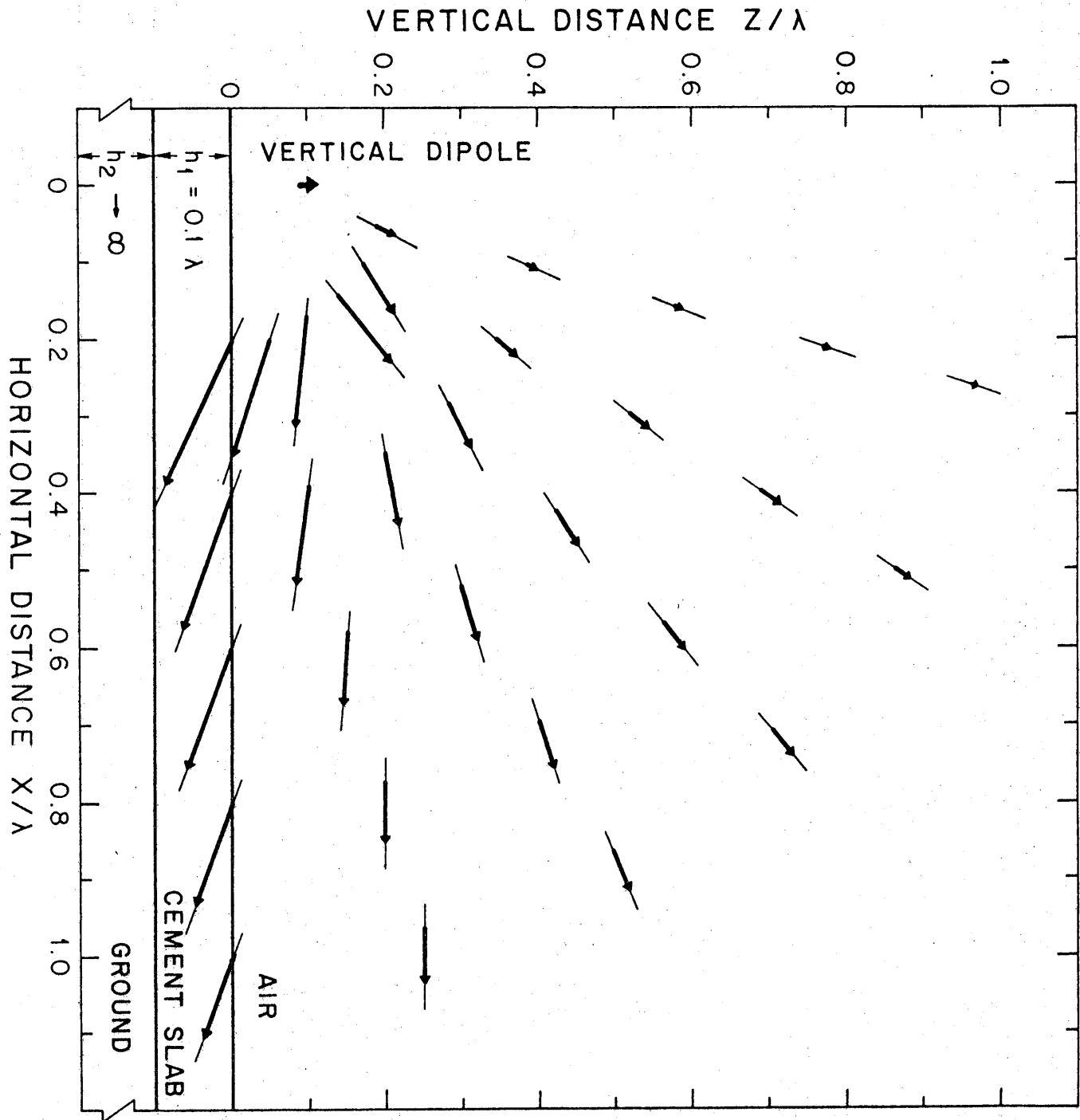


Figure 7. Magnitude and direction of the normalized time average power density distribution for a vertical dipole source (1 cm of arrow length  $\equiv$  unity):  $f = 300$  MHz,  $\lambda = 1$  meter,  $n_1 = 1.732 + i0.0346$  and  $n_2 = 3.1637 + i0.0947$ .

to a unity) also decays faster than  $R_{11}^{-2}$ . This situation can be attributed partly to the rapid decay of the inductive field near the source region and partly to the dissipation of the electromagnetic field underneath the slab surface. On the slab surface the power flux, or the Poynting vector is generally tilted into the surface.

A similar plot of the power flux for a horizontal dipole source shows some remarkably different features. As seen in Fig. 8 and for observation in the plane of the dipole, the power flux no longer vanishes along the dipole axis. Furthermore, in the region close to the dipole on the slab the direction of the vector also not always points toward the slab surface. Since the dipole field in the absence of the two-layer earth is known to be small in this direction, the phenomenon undoubtedly is caused by the scattered field in the source region near the slab surface. For observation points in the plane perpendicular to the dipole ( $\theta = 90^\circ$ ), Fig. 9 shows that the power flux now behaves in a more predictable manner.

To further investigate the field behavior on the slab surface, Figures 10 and 11 show, respectively, the magnitude and the tilt angle of the normalized power flux as a function of observation distances. It is seen that, except for the region close to the source, the tilt angle, or the direction of the Poynting vector of a horizontal dipole observed in the plane of the dipole, approaches to that of the vertical dipole, while the tilt angle observed in the perpendicular plane approaches to a different limit. As it is well known in the theory of ground wave propagation [Wait, 1962], the tilt angle depends, in addition to the refractive indices of the different media, upon mainly the type of polarization of the impinging wave, rather than the exact orientation

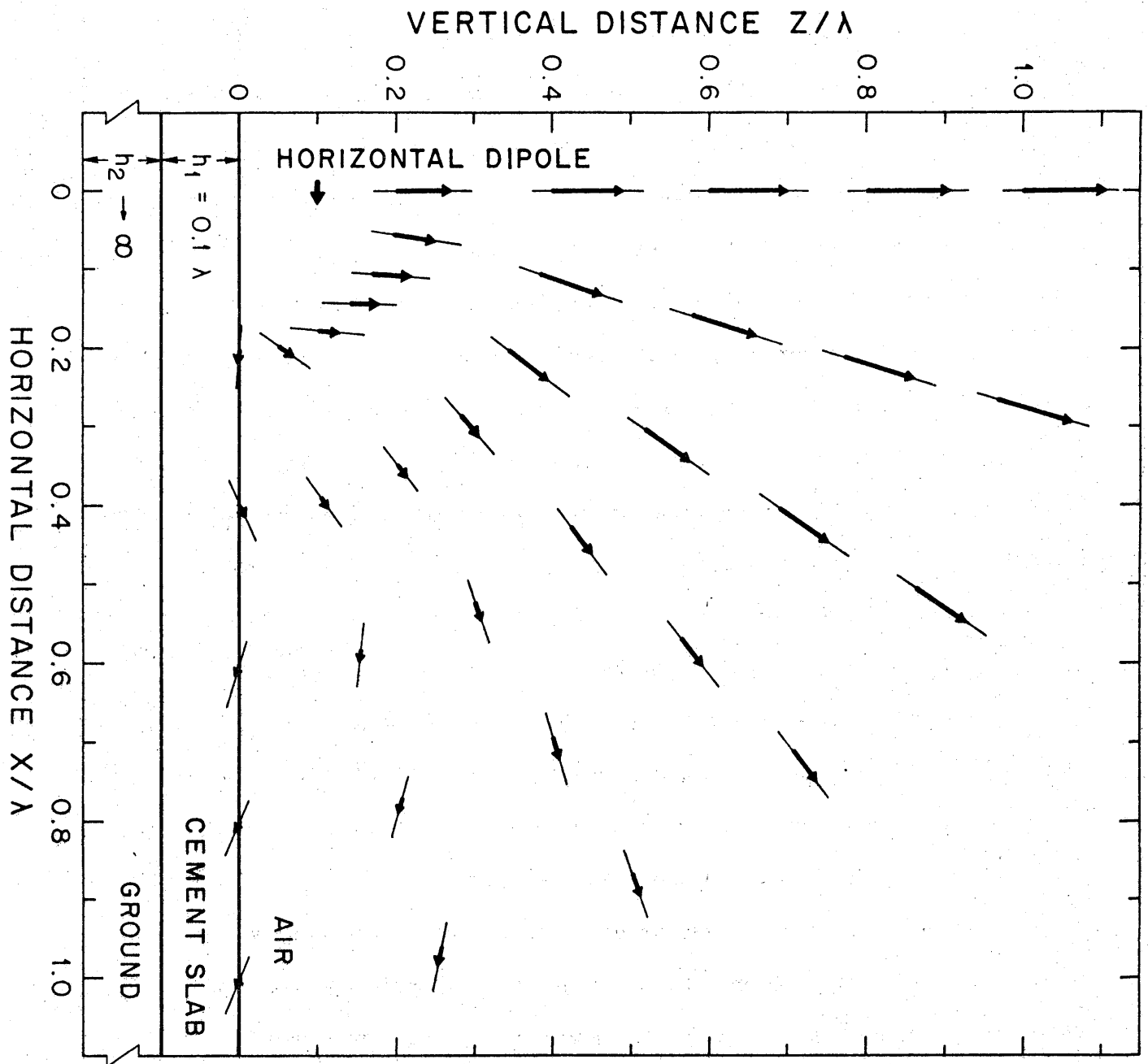


Figure 8. Magnitude and direction of the normalized time-average power density distribution for a horizontal dipole source in the plane of incidence;  $\phi = 0^\circ$ , (1 cm of arrow length  $\equiv$  unity),  $f = 300$  MHz,  $\lambda = 1$  meter,  $n_1 = 1.732 + i0.0346$  and  $n_2 = 3.1637 + i0.0947$ .

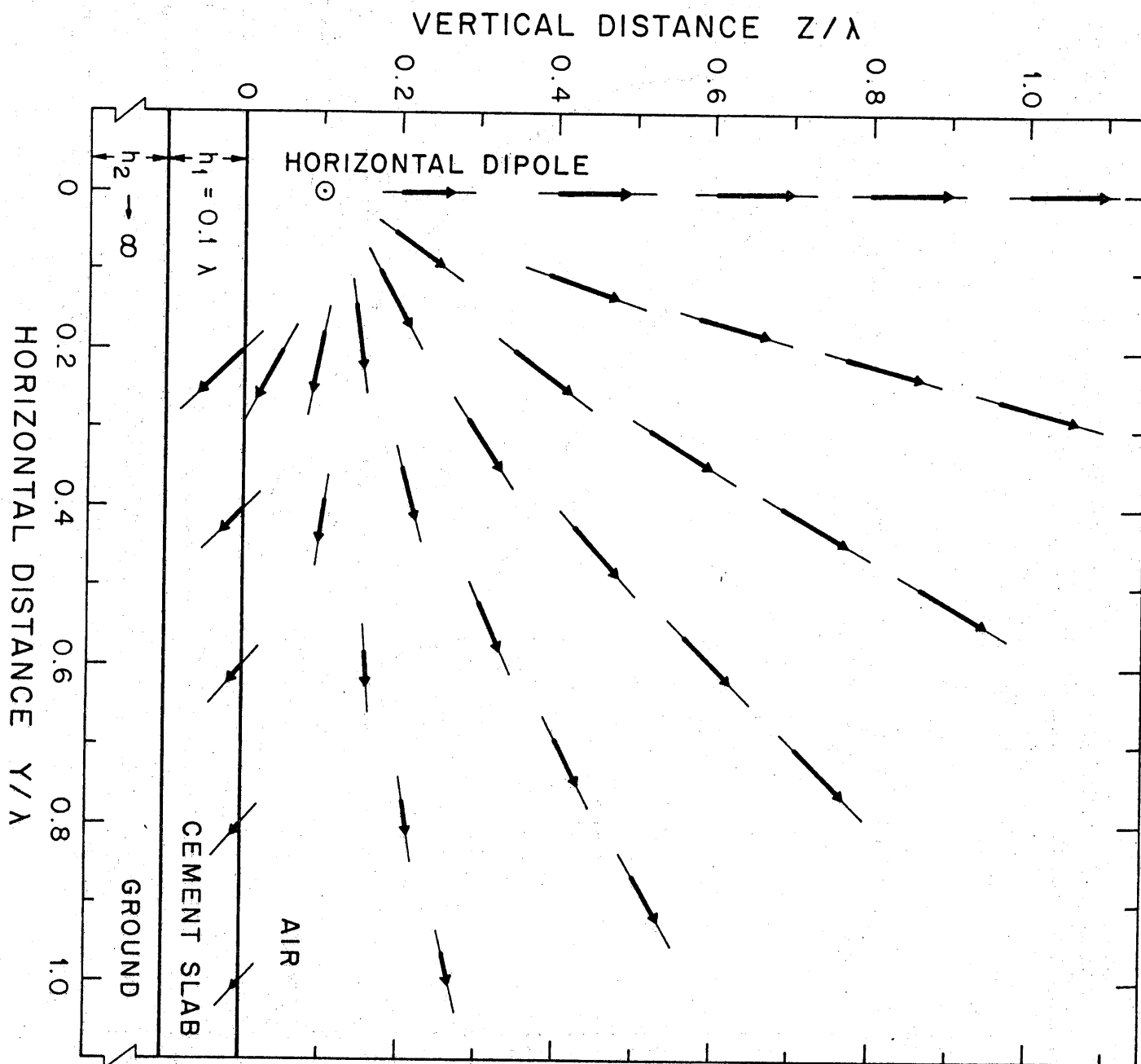


Figure 9. Magnitude and direction of the normalized time-average power density distribution in the plane perpendicular to the dipole;  $\phi = 90^\circ$ , (1 cm of arrow length  $\equiv$  unity),  $f = 300$  MHz,  $\lambda = 1$  meter,  $n_1 = 1.732 + i0.0346$  and  $n_2 = 3.1637 + i0.0947$ .



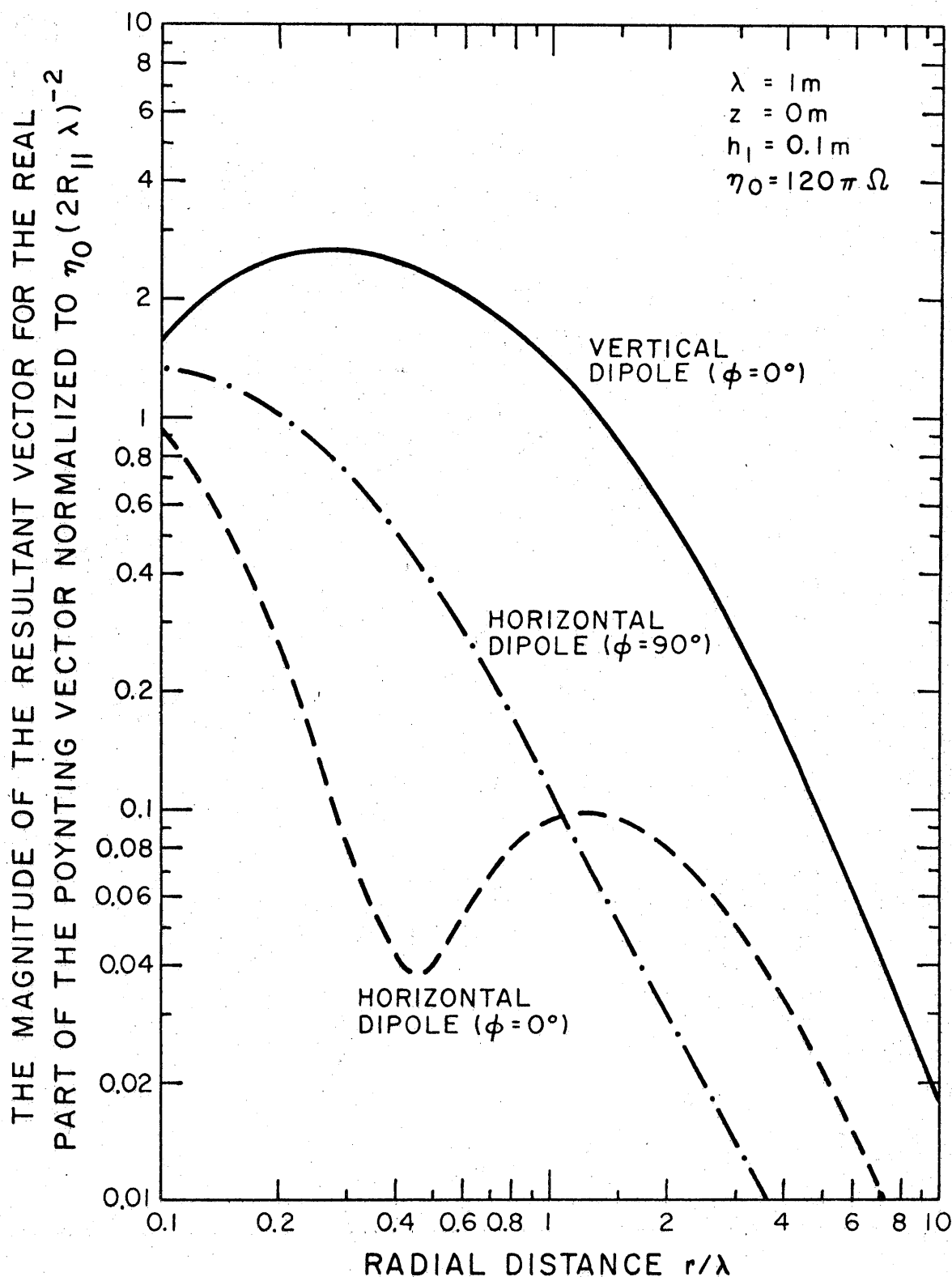


Figure 10. Magnitude of the normalized time-average power density on the slab surface as a function of observation distance for a vertical dipole ( $\phi = 0^\circ$ ), a horizontal dipole ( $\phi = 0^\circ$ ) and a horizontal dipole ( $\phi = 90^\circ$ ).

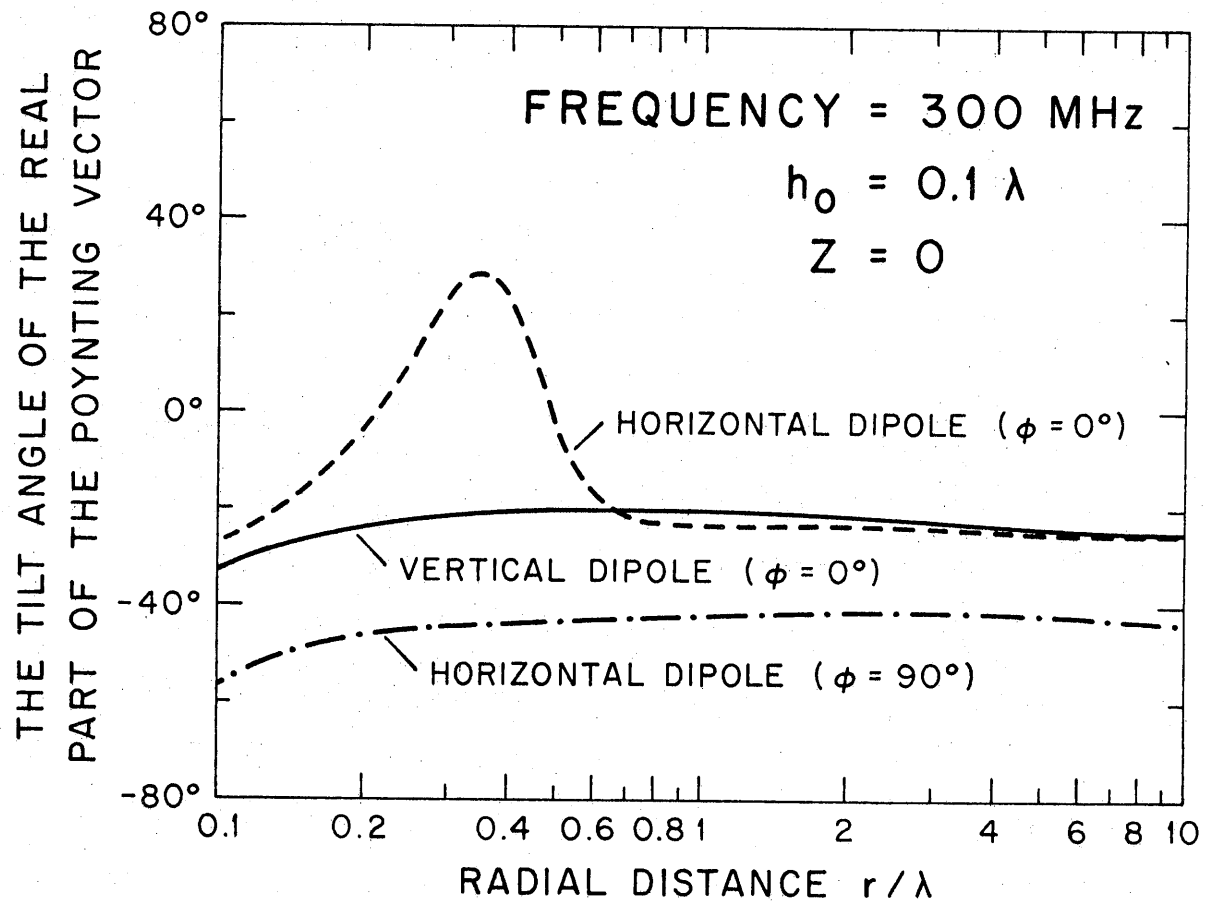


Figure 11. Tilt angle of the time average Poynting vectors on the slab surface versus the normalized radial distance for a vertical dipole ( $\phi = 0^\circ$ ), a horizontal dipole ( $\phi = 0^\circ$ ) and a horizontal dipole ( $\phi = 90^\circ$ ).

of the dipole source. Thus, the tilt angle of both the vertical and the horizontal dipole observed in the plane of the dipole should approach to the wave tilt of a TM-wave, while the other approaches to the wave tilt of a TE-wave.

As shown in Fig. 10, the change in the magnitude of the power flux along the slab surface for the three dipole arrangements as a function of observation distance also differs significantly. In the case of a horizontal dipole, a minimum and then a maximum are observed as one moves away in the plane of the dipole. The tip occurs at  $r \approx .45$  or for an observation angle of  $77.5^\circ$ . However no such tip is observed in the other two arrangements. To examine the occurrence of this tip in detail, we include in Figure 12, the magnitude of the power flux versus observation distance for several slab thickness, including  $h_1 = 0$  which corresponds exactly to the case of a homogenous earth in the absence of the slab. It is shown in this case, the tip occurs at  $r \approx .65$ . As the slab thickness increases the location of the tip moves toward the source until  $h_1 = .3$  m; thereafter, a second tip emerges. Figures 13 and 14 show the change in the magnitude of the power flux for the other two dipole arrangements. However no drastic change in the magnitude of the power flux is observed as one moves away on the slab surface in these cases.

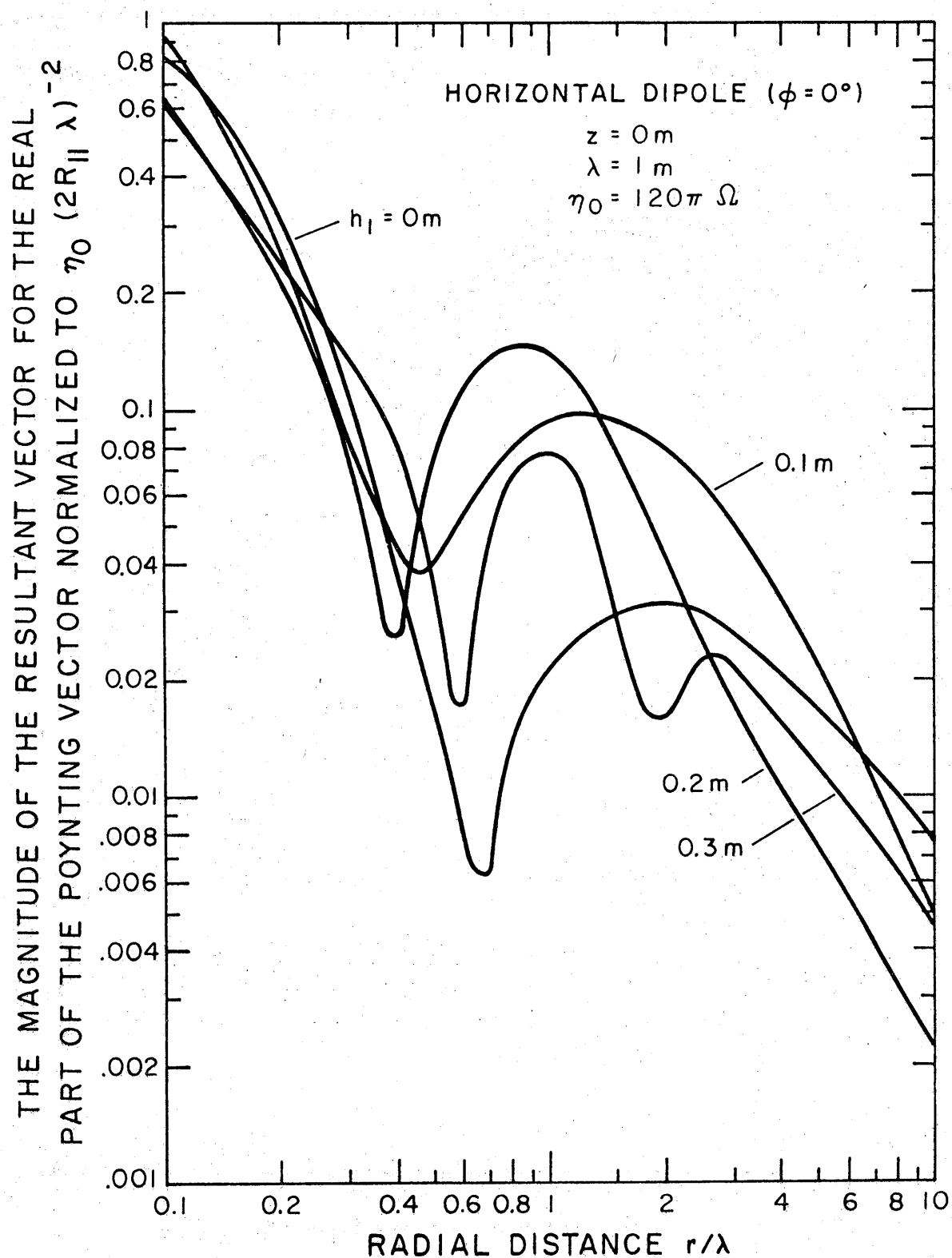


Figure 12. Magnitude of the normalized time average power density on the slab surface for a horizontal dipole source observed in the plane of incidence ( $\phi = 0^\circ$ )

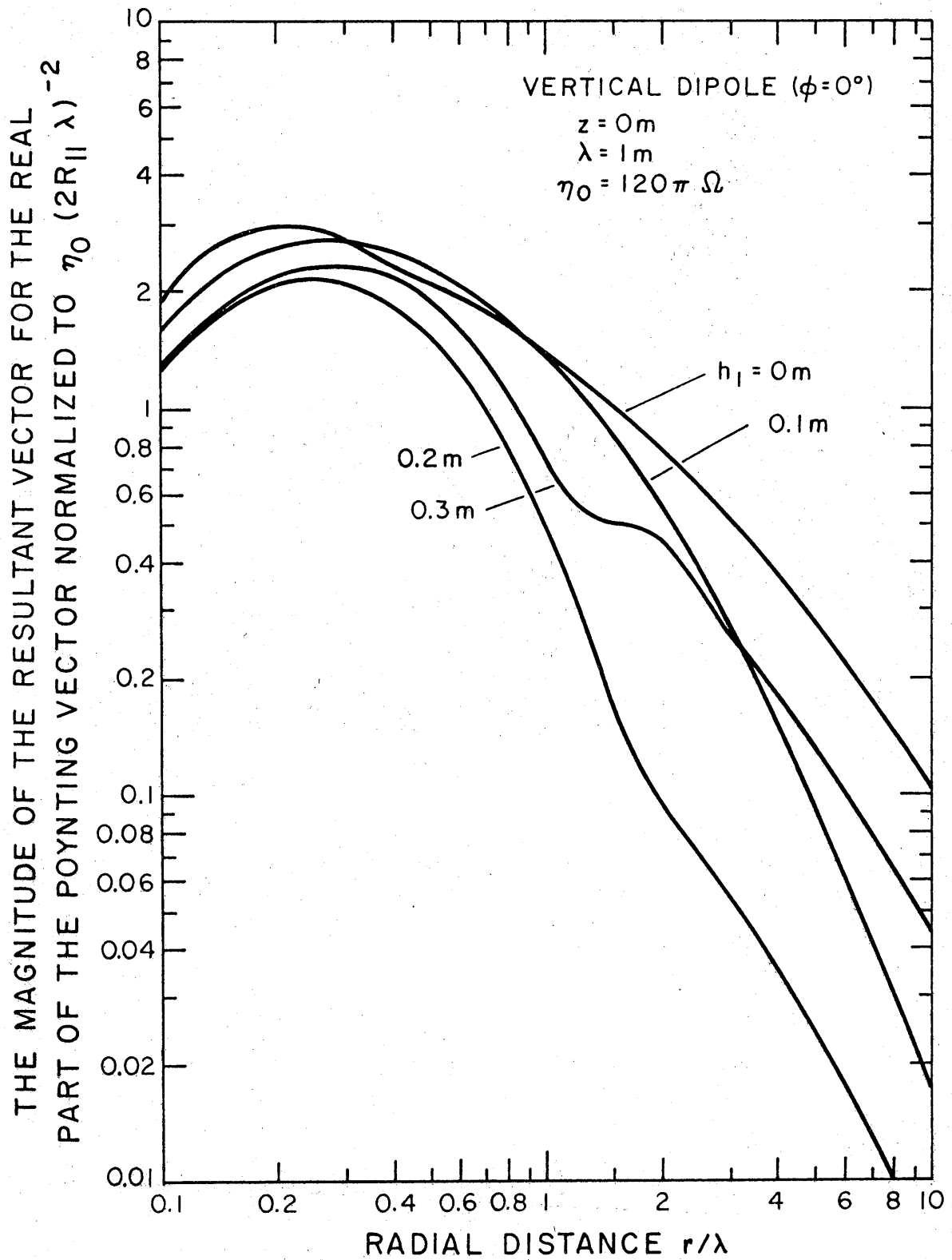


Figure 13. Magnitude of the normalized time-average power density on the slab surface for a vertical dipole source.

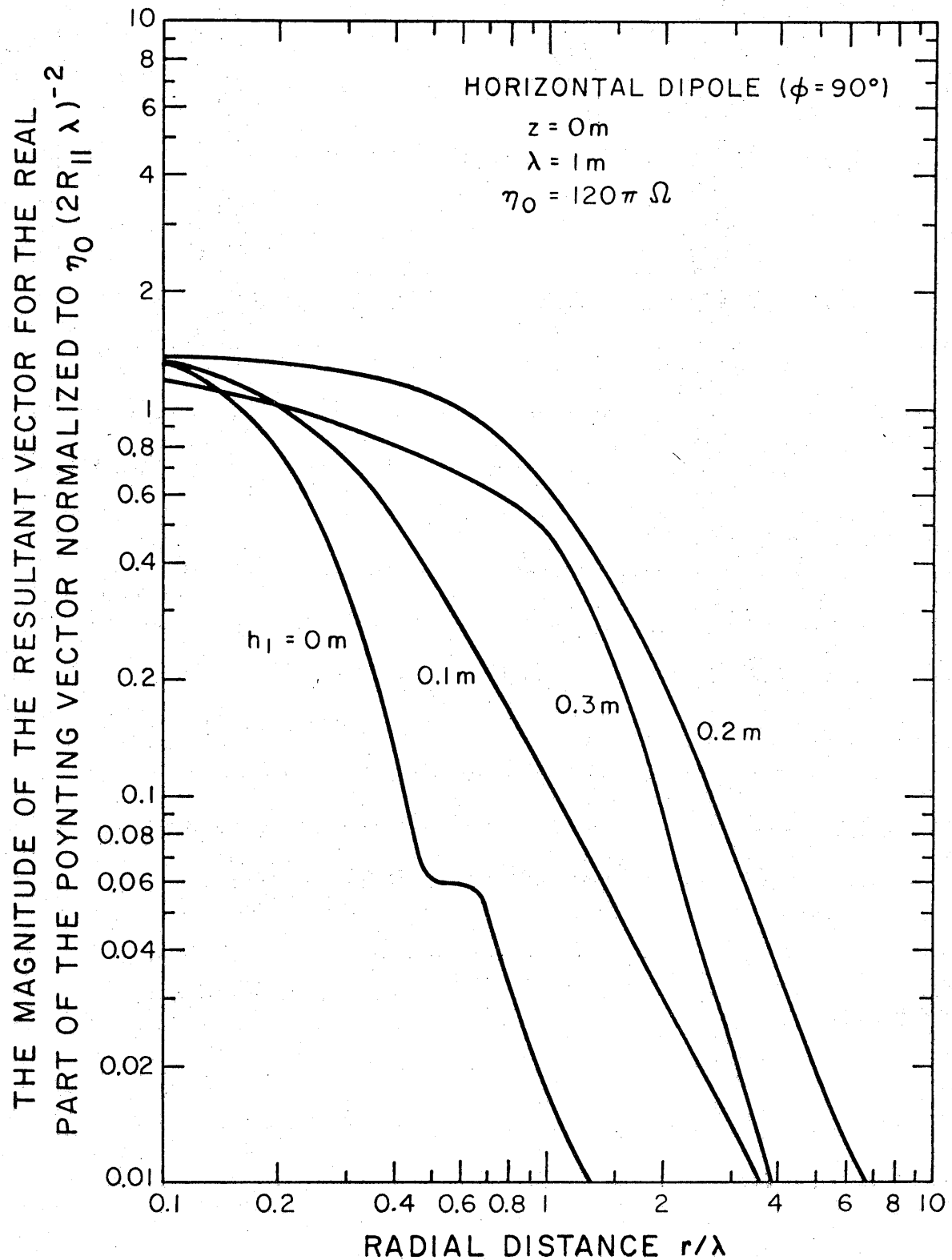


Figure 14. Magnitude of the normalized time-average power density on the slab surface for a horizontal dipole source observed in the plane perpendicular to the dipole ( $\phi = 90^\circ$ )

## 6. Conclusion

In this report a numerical program is devised which computes all components of the electromagnetic field simultaneously by integrating an array of functions along the real axis in the complex  $\alpha$ -plane. Increased efficiency is obtained with the incorporation of the quasi-static and asymptotic approximations. The inclusion of a root finder in the program also makes it possible to integrate efficiently for the case when a pole is close to the path of integration. It should be noted, however, for the typical parameters we have studied, the poles were sufficiently away from the real axis so that no particular effort is needed. In principle, we can also extend the method to treat the case involving more than one pole.

The computer program is also capable of finding the field for a semi-infinite half-space problem. In this case, the slab width  $h_1$  will be either zero or infinity. However, if quasi-static approximation is used, the case of  $h_1$  approaches infinity should be chosen. The reason for this restriction is that the approximations we have used assumes a finite  $h_1$  so that beyond a certain value of  $\alpha_0$  analytical expression for the integral can be obtained.

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## APPENDIX A

In this Appendix, the analytical expression for  $V_\ell^{(2)}$ ,  $\ell=1,2$  given in (50) is derived.

$$V_\ell^{(2)} = \int_{\alpha_0}^{\infty} [F_\ell(\alpha) - F_{\ell q}(\alpha)] e^{-\gamma_0 b} J_0(\alpha \rho) \alpha d\alpha \quad (\text{A-1})$$

Now, if we use the choice of  $\alpha_0$  to be large such that  $\tanh|\gamma_1 H_1| \approx 1$ , then the expressions for  $N_0$  and  $K_0$  in (8) and (9) will reduce to  $\gamma_1$  and  $\gamma_1/n_1^2$  respectively. Therefore  $V_1^{(2)}$  and  $V_2^{(2)}$  can be written as

$$V_1^{(2)} \approx \int_{\alpha_0}^{\infty} \left[ \frac{1}{\gamma_0 + \gamma_1/n_1^2} - \frac{2n_1^2}{(n_1^2 + 1)\gamma_0} \right] e^{-\gamma_0 b} J_0(\alpha \rho) \alpha d\alpha \quad (\text{A-2})$$

and

$$V_2^{(2)} \approx \int_{\alpha_0}^{\infty} \left[ \frac{1}{\gamma_0 + \gamma_1} - \frac{1}{\gamma_0} \right] e^{-\gamma_0 b} J_0(\alpha \rho) \alpha d\alpha \quad (\text{A-3})$$

By expanding in the inverse power of  $\gamma_0$ ,  $V_\ell^{(2)}$ ,  $\ell=1,2$ , can be approximated to the following form:

$$V_\ell^{(2)} = C_\ell V \quad \ell = 1, 2 \quad (\text{A-4})$$

where

$$V = \int_{\alpha_0}^{\infty} e^{-\gamma_0 b} J_0(\alpha \rho) \alpha \gamma_0^{-3} [1 + O(\gamma_0^{-2}) + \dots] d\alpha \quad (\text{A-5})$$

The constants  $C_1$  and  $C_2$  are given by

$$C_1 = -2n_1^2/(n_1^2 + 1)^2$$

and

$$C_2 = (n_1^2 - 1)/4$$

Thus if we just keep the leading terms of (A-5) and the assumption that  $\alpha_0 \gg 1$  then

$$V \approx \int_{\alpha_0}^{\infty} e^{-\alpha b} J_0(\alpha \rho) \frac{d\alpha}{\alpha^2}$$

The above integral can be evaluated by taking the derivatives with respect to  $\rho$  and then splitting up the integral into two parts; one has the limit of 0 to infinity and the other from 0 to  $\alpha_0$ .

$$\frac{\partial V}{\partial \rho} = -\left\{ \int_0^{\infty} e^{-\alpha b} J_1(\alpha \rho) \frac{d\alpha}{\alpha} - \int_0^{\alpha_0} e^{-\alpha b} J_1(\alpha \rho) \frac{d\alpha}{\alpha} \right\}$$

The first integral can be found exactly (Gradshteyn and Ryzhik [1965])

$$\int_0^{\infty} e^{-\alpha x} J_\nu(\beta x) \frac{dx}{x} = \frac{(\sqrt{\alpha^2 + \beta^2} - \alpha)^\nu}{\nu \beta^\nu} \quad \text{Re } \nu > 0, \text{ Re } \alpha > |\text{Im } \beta| \quad (\text{A-6})$$

therefore

$$\int_0^{\infty} e^{-\alpha b} J_1(\alpha \rho) \frac{d\alpha}{\alpha} = (R-b)\rho^{-1} = \rho(R+b)^{-1}$$

However the second integral has been evaluated approximately by using Taylor expansion of two variables  $b$  and  $\rho$  around  $b, \rho = 0$

$$\int_0^{\alpha_0} e^{-\alpha b} J_1(\alpha \rho) \frac{d\alpha}{\alpha} \approx \frac{\alpha_0}{2} \rho + O(\rho^2)$$

After substituting the values of the first and second term in (A-6), we can integrate back with respect to  $\rho$  which will lead to

$$V = -R + b \ln(R+b) + \frac{\alpha_0}{2} \rho^2 - C(b)$$

where  $C(b)$  is a function of  $b$  only and is given by

$$-C = b - b \ln 2b + \frac{E_2(\alpha_0 b)}{\alpha_0}$$

Here  $E_2$  is the exponential integral of order 2 and is given by (Abramowitz and Stegun [1964]).

$$E_2(\alpha_o b) = e^{-\alpha_o b} + \gamma(\alpha_o b) + \alpha_o b \ln(\alpha_o b) + \alpha_o b \sum_{n=1}^{\infty} \frac{(-1)^n (\alpha_o b)^n}{n!}$$

where  $\gamma$  is Euler's constant .5772.

Since  $R \ll 1$ , terms of the order  $R^2$  or greater will be ignored. Also, it should be noted that  $\alpha_o b$  and  $\alpha_o \rho$  are small compared to the leading terms that are of the order  $R^{-1}$ . Thus  $V$  can be written in a simpler form as

$$V = -R + b[\gamma + \ln(\alpha_o/2)] + \frac{e^{-\alpha_o b}}{\alpha_o} + b \ln(b + R) \quad (A-7)$$

The substitution of (A-7) into (A-4) then gives the analytical expression for the correction terms  $V_{\ell}^{(2)}$ ,  $\ell = 1, 2$  as indicated in (50).

## APPENDIX B

In this appendix, approximate solutions for  $V_3^{(j)}$ , ( $j=1,2$  and  $3$ ) is obtained as  $R$  approaches zero. As in Appendix A, we assume that  $\alpha_0$  is large compared to  $H_1$  so that  $\tanh|\gamma_1 H_1| \approx 1$  can be used. However the product of  $\alpha_0 R$  is still assumed to be small compared to 1 as  $R \rightarrow 0$ . The leading term  $V_3^{(1)}$  in (54) is written here as

$$V_3^{(1)} = B_3 \cos \phi \frac{\partial}{\partial \rho} \int_b^\infty db \int_0^\infty e^{-\gamma_0 b} J_0(\alpha \rho) \alpha \gamma_0^{-1} d\alpha \quad (B-1)$$

The integral with respect to  $\alpha$  is known as  $G_{12} = e^{iR_{12}}/R_{12}$ . If we now split up the integration over  $b$  into two parts, one runs from 0 to  $\infty$  and the other from 0 to  $b$ , the first integral then reduces to the Hankel function form  $\frac{\pi i}{2} H_0^{(1)}(\rho)$ . However, for the second integral, Taylor expansion of  $G_{12}$  will be used since  $R_{12}$  is very small. After integrating the first three terms of the expansions, it is easy to show that  $V_3^{(1)}$  can be given as

$$V_3^{(1)} \approx B_3 \cos \phi \left\{ -\frac{\pi i}{2} H_1^{(1)}(\rho) + \frac{b}{\rho R} + \frac{\rho}{2} \sinh^{-1}(b/\rho) \right\} \quad (B-2)$$

It should be noted that in obtaining the above result the differentiation with respect to  $\rho$  is applied after the integration over  $b$  is performed. Expression for  $V_3^{(1)}$  can be further simplified if we replace the Hankel function by its small argument expansion to yield

$$V_3^{(1)} = -B_3 \rho \cos \phi \left\{ [R(R+b)]^{-1} - .5 \ln(R+b) - \frac{1}{2}(\gamma - \frac{1}{2} - \pi i/2 - \ln 2) \right\} \quad (B-3)$$

where  $\gamma = .5772$  is Euler's constant.

The second term from (54) that needs to be evaluated analytically is  $V_3^{(2)}$  and is given by

$$V_3^{(2)} = B_3 \cos \phi \frac{\partial}{\partial \rho} \int_0^\infty \left[ \frac{1}{\gamma_1^2} - \frac{1}{\gamma_o^2} \right] e^{-\gamma_o b} J_o(\alpha \rho) \alpha d\alpha \quad (B-4)$$

Again, the integral can be divided into two parts, one runs from 0 to  $\alpha_o$  and the other from  $\alpha_o$  to  $\infty$  and approximation techniques similar to the ones given in Appendix A can be applied here. It should be noted that the outcome of the integration should be independent of  $\alpha_o$ . Now  $V_3^{(2)}$  can be written as

$$V_3^{(2)} = V_{31}^{(2)} + V_{32}^{(2)} \quad (B-5)$$

where

$$V_{31}^{(2)} = B_3 \cos \phi \frac{\partial}{\partial \rho} \int_0^{\alpha_o} \left[ \frac{1}{\gamma_1^2} - \frac{1}{\gamma_o^2} \right] e^{-\gamma_o b} J_o(\alpha \rho) \alpha d\alpha \quad (B-6)$$

and

$$V_{32}^{(2)} = B_3 (n_1^2 - 1) I \cos \phi \quad (B-7)$$

$$I = \frac{\partial}{\partial \rho} \int_{\alpha_o}^\infty e^{-\gamma_o b} J_o(\alpha \rho) \frac{\alpha d\alpha}{(\gamma_o \gamma_1)^2} \approx \frac{\partial}{\partial \rho} \int_{\alpha_o}^\infty e^{-\gamma_o b} J_o(\alpha \rho) \frac{\alpha d\alpha}{\gamma_o^4} \quad (B-8)$$

In writing  $V_{32}^{(2)}$  above, we have replaced  $\left( \frac{1}{\gamma_1^2} - \frac{1}{\gamma_o^2} \right)$  by  $[(n_1^2 - 1)/(\gamma_o \gamma_1)^2]$ .

Then, we have used the assumption that  $\alpha_o$  is large so that  $\gamma_1$  would be replaced by  $\gamma_o$ . Thus, the differentiation of  $I$  with respect to  $b$  is known as  $-\frac{\partial V}{\partial \rho}$ , where  $V$  is given by (A-5) and known explicitly in (A-7).

Hence,  $\frac{\partial I}{\partial \rho}$  can be written as

$$\frac{\partial I}{\partial b} \approx \frac{\rho}{R} - \frac{b}{\rho} \left( 1 - \frac{b}{R} \right)$$

Integrating the above expression to get the value of  $I$  as

$$I = \frac{1}{2} [\rho \sinh^{-1}(b/\rho) + b\rho (R + b)^{-1} - K(\rho)] \quad (B-9)$$

and the integration constant  $K(\rho)$  is determined from the condition at  $b = 0$

$$K(\rho) = \int_{\alpha_0}^{\infty} J_1(\alpha\rho) \alpha^2 \frac{d\alpha}{\gamma_0^4}$$

$$\approx \int_{\alpha_0}^{\infty} J_1(\alpha\rho) \frac{d\alpha}{\alpha^2}$$

It is then not difficult to show that  $K(\rho)$  satisfies the first order differential equation

$$\frac{\partial K}{\partial \rho} + \frac{K}{\rho} = \int_{\alpha_0}^{\infty} J_0(\alpha\rho) \frac{d\alpha}{\alpha}$$

The integral on the right side of the differential equation can be replaced by a two term expansion, ignoring the series terms which are of the order  $\rho^2$  or greater [Abramowitz, page 481, Eq. 11.1.20, 1964]. Thus the differential equation reduces to the following form

$$\frac{\partial K}{\partial \rho} + \frac{K}{\rho} = -\gamma - \ln(\alpha_0 \rho/2)$$

which has a known solution of the form

$$K(\rho) = -\frac{\rho}{2} [\gamma + \ln(\alpha_0/2) - \frac{1}{2}] - \frac{\rho}{2} \ln \rho$$

where  $\gamma$  here is Euler's constant. The substitution of the above value of  $K(\rho)$  into (B-9) and then the value of  $I$  into (B-7) will give  $V_{30}^{(2)}$  as

$$V_{32}^{(2)} = \frac{(n_1^2 - 1)}{2} \rho B_3 \cos \phi [\ln(b+R) + b(R+b)^{-1} + (\gamma - \frac{1}{2} - \ln 2 + \ln \alpha_0)] \quad (B-10)$$

Clearly, the result we have gotten for  $V_{32}^{(2)}$  is dependent on  $\alpha_0$  and this term should cancel out with the contribution from  $V_{31}^{(2)}$  up to the order of

$R^2$ . Since  $b$  and  $\rho$  are both small, a two variable Taylor expansion around  $b, \rho = 0$  gives approximate expression of  $V_{31}^{(2)}$  and is given by

$$V_{31}^{(2)} \approx B_1 \rho \cos \phi \int_0^{\alpha_0} \alpha^3 \left[ \frac{1}{\gamma_1} - \frac{1}{\gamma_0} \right] d\alpha \quad (B-11)$$

The evaluation of the integral can be readily carried out, provided the integration path is understood as being indented into the lower half-plane at  $\alpha = 1$ .

$$V_{31}^{(2)} = -\frac{1}{4} B_3 \cos \rho \left[ n_1^2 \ln \left( \frac{\alpha_0^2 - n_1^2}{\alpha_0^2 - 1} \right) + (n_1^2 - 1) \ln(\alpha_0^2 - 1) - n_1^2 \ln n_1^2 + \pi i (n_1^2 - 1) \right] \quad (B-12)$$

Thus, with the assumption that  $\alpha_0 \gg |n_1|$  we finally have the resultant expression in the form of

$$V_{31}^{(2)} = \frac{(n_1^2 - 1)}{2} B_3 \rho \cos \phi \left[ -\ln \alpha_0 + \frac{n_1^2}{(n_1^2 - 1)} \ln n_1 - \frac{\pi i}{2} \right] \quad (B-13)$$

Substitution of the expressions for  $V_{31}^{(2)}$  in (B-13) and  $V_{32}^{(2)}$  in (B-10) into (B-5) now yields the result

$$V_3^{(2)} = \frac{(n_1^2 - 1)}{2} B_3 \rho \cos \phi \left\{ \ln(b+R) + b(R+b)^{-1} + \left( \gamma - \frac{1}{2} - \pi i/2 - \ln 2 \right) + \frac{n_1^2}{(n_1^2 - 1)} \ln n_1 \right\} \quad (B-14)$$

which is then independent of the parameter  $\alpha_0$  that we somewhat arbitrarily have chosen.

The last integral needs to be evaluated is  $V_3^{(3)}$  in (54). Since  $\alpha_0$  is large such that  $\tanh|\gamma_1 H_1| \approx 1$ , then  $N_0$  and  $K_0$  will be replaced by  $\gamma_1$  and  $\gamma_1/n_1^2$  respectively. Thus  $V_3^{(3)}$  can be written here as

$$V_3^{(3)} = B_3 \cos \phi \frac{\partial}{\partial \rho} \int_{\alpha_0}^{\infty} \left[ \frac{2(n_1^2 - 1)}{n_1^2(\gamma_0 + \gamma_1)(\gamma_0 + \gamma_1/n_1^2)} - \frac{(n_1^2 - 1)}{(n_1^2 + 1)\gamma_1^2} \right] e^{-\gamma_0 b} J_0(\alpha \rho) \alpha d\alpha \quad (B-15)$$

If we now approximate  $\gamma_1 \approx \gamma_0 + \frac{1}{2} \frac{(n_1^2 - 1)}{\gamma_0}$ , the leading term of  $V_3^{(3)}$  in

(B-17) can be shown to be associated with the integral I given in (B-8) which is evaluated in (B-9). Consequently, we have

$$V_3^{(3)} = -C_3 \rho \cos \phi [\ln(b+R) + b(R+b)^{-1} + (\gamma - \frac{1}{2} - \ln 2 - \ln \alpha_0)] \quad (B-16)$$

where

$$C_3 = (3n_1^2 + 1) [(n_1^2 - 1)/(n_1^2 + 1)]^2 / 8$$



## APPENDIX C

A computer program was developed to find the electromagnetic field response of a tiled dipole above a finitely conducting two layered earth according to the numerical scheme described in Section 3, with provision for the asymptotic and quasi-static calculation as explained in Section 4. Flow chart of the program is shown in Figure 15. The program mainly consists of three subroutines called QSTATC, RESULT and ASMPT, each of which is capable of calculating field components for different ranges of observations in space.

The subroutine RESULT is used to integrate along the real axis of the complex  $\alpha$ -plane for a given integrand. It follows the same steps given in Section 3, where the integration has been split up into two different regions as given in (34). As mentioned before, a provision is made when the location of the pole is close to the path of integration. By drawing a circle of influence with a radius  $\alpha_s = |\alpha_p - 1|$  and centered at  $\alpha_p$ , we can integrate separately the interval within this circle in order to insure good numerical accuracy. Thus  $\alpha_s$  determines how the integration path should be split up, for example if  $\alpha_s \geq 1$  then the integration will proceed exactly according to (34). But if  $\alpha_s < 1$  then the path of integration will be subdivided. Obviously our path of integration is taken beneath the branch cut for  $\alpha$  between 0 and 1 and the pole could have stronger influence if it is close to or beyond the branch point at  $\alpha = 1$ . Usually the situation where the pole is close to the branch point at  $\alpha = 1$ , occurs when we have a two region conducting half-space (such as air and earth). For a typical application of a concrete slab above a homogenous earth and for the frequency range (100-1000 MHz), the poles are actually not very close to the path of integration as shown in Table 3.

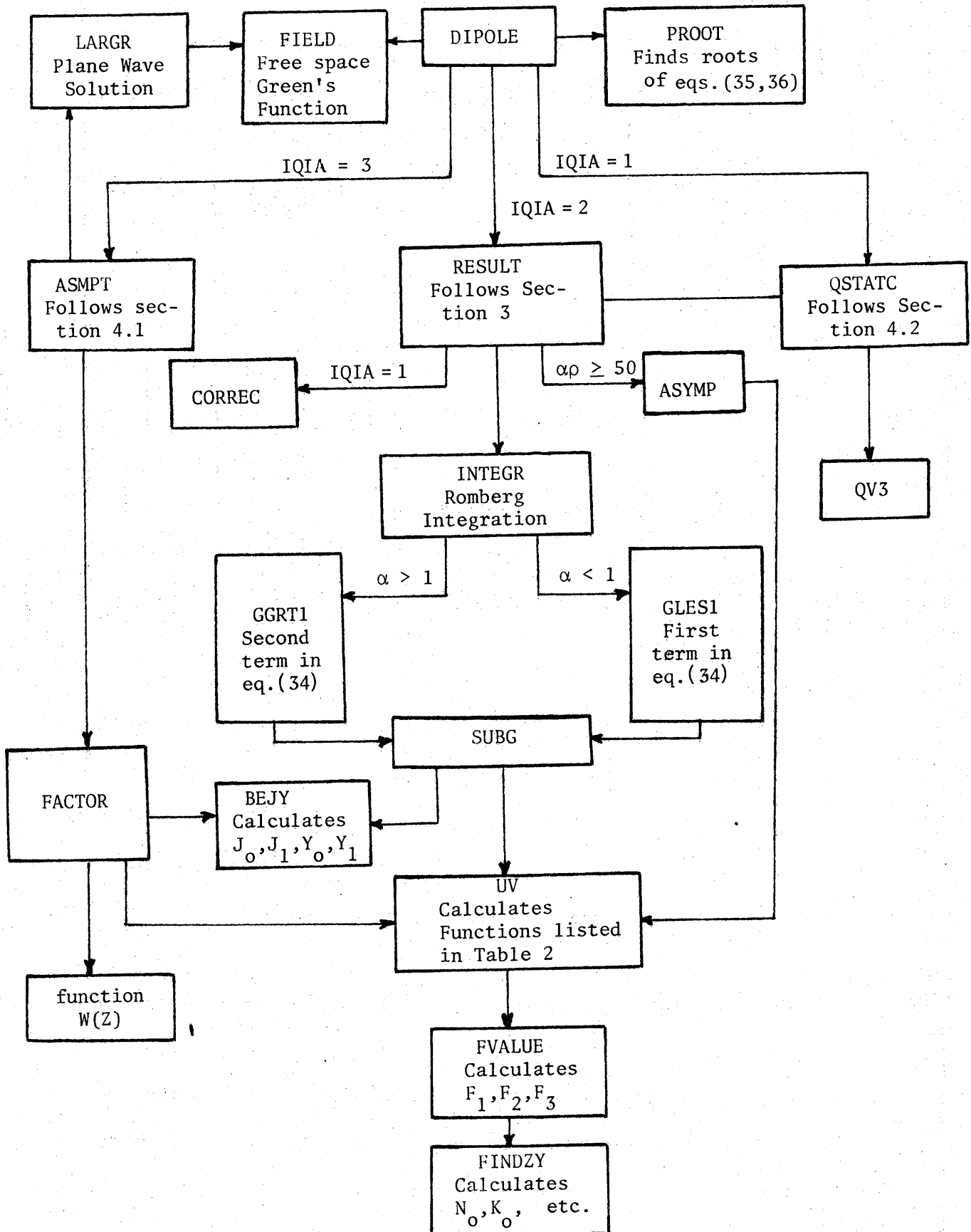


Figure 15. A flow chart of the computer program

However, we have left this subdivision criteria in the program so that the program can be a general purpose one. Our program without further modification cannot handle the cases where the poles are directly on the real axis which corresponds to lossless slab above a perfectly conducting sheet. But in most of the cases which involves losses in both media the poles usually move upward away from the real axis. A root finder called PROOT is developed which uses the poles of a lossless slab above a perfectly conducting sheet as a basis to march toward the roots for a lossy slab and earth. A combination of bisectional and Newton's methods are used to search the complex roots of (35) and (36). In Figure 16, we have shown the flow chart of the root finder, where at first the subroutine ROOT will search the real roots of the lossless slab above a perfectly conducting sheet then these roots (if any) will be used in ZROOT to search for the complex roots of a lossy slab above a finitely conducting earth.

Except for the region nearby the pole the two integrals in (34) are further broken up into segments where numerical integration based upon a modified Romberg scheme is performed. Segment interval is determined either from the nature cycle of the Bessel functions, i.e.  $\Delta\alpha \approx 2\pi/\rho$ , or from the decay rate of the exponential function, i.e.  $\Delta\alpha \approx 3/(Z+H_0)$ . Obviously the number of integrations and the computation time increases when  $\rho$  and  $(Z + H_0)$  are either very small or very large. In such cases, the program is then switched to the quasi-static and asymptotic routines even though the normal integration method can be performed.

We now discuss the type of convergence criteria we have adopted for the truncation of the infinite integral in (34). Judging from the expression for the integrand as given in (30), it is obvious that one can simply integrate until the argument of the exponential function  $\gamma_0(Z+H_0)$  is large

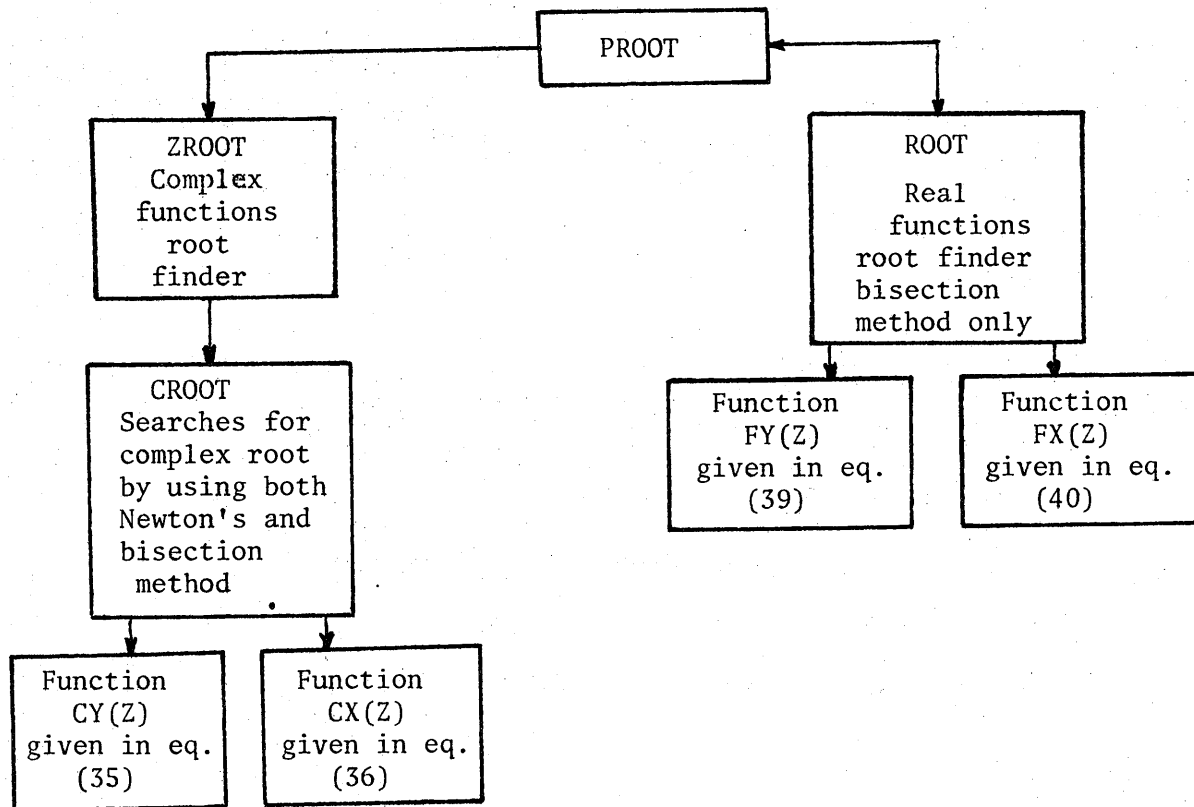


Figure 16. A flow chart of the root finder

enough, say 12, so that the remainder of the integration will be of the order  $10^{-7}$  or smaller. However, this criterion becomes less effective for observation near the surface when  $(Z + H_0)$  is small. In that case, we switch the truncation criterion to one that depends on the argument of the Bessel function  $\alpha\rho$ , where  $\rho = k_0 r$  and  $r$  is the horizontal distance from the source to the observation point. When  $\alpha\rho$  reaches a certain large number, say 50 or more, we can replace the Bessel function by its asymptotic form (Abramowitz [1964]). Then the remainder of the integral can be evaluated analytically by an asymptotic series. Since each term of the series decreases by the factor  $(\alpha\rho)^{-1}$  from its previous term, we used a two term expression and estimate the error bound. The truncation is then determined by a specified accuracy of five digits. These remainder terms can be deduced from (30) and typically given as follows:

$$T_m(\alpha_t) = \int_{\alpha_t}^{\infty} F(\alpha) [\cos \chi - P(\alpha) \sin \chi] d\alpha \quad m = 0, 1 \quad (C-1)$$

where  $\chi = (\alpha\rho - \frac{m\pi}{2} - \frac{\pi}{4})$ ,  $P(\alpha) = \frac{4m^2-1}{8\alpha\rho}$  and  $\alpha_t$  is the limit where the Bessel function can be replaced by its asymptotic form.  $F(\alpha)$  is given by

$$F(\alpha) = (2/\pi\alpha\rho)^{\frac{1}{2}} \alpha G(\alpha) / \gamma_0$$

and  $G(\alpha)$  is a typical function listed in Table 2. Now, if we twice perform the integration by parts in C-1,  $T_m(\alpha_t)$  will reduce to approximately

$$T_m(\alpha_t) = -\frac{\sin \chi_0}{\rho} F(\alpha_t) - \frac{\cos \chi_0}{\rho^2} \left. \frac{dF}{d\alpha} \right|_{\alpha=\alpha_t} - \frac{(4m^2-1)}{8\alpha_0} \frac{\cos \chi_0}{\rho^2} F(\alpha_t) + O(\rho^{-3}) \quad (C-2)$$

where

$$\chi_0 = (\alpha_t \rho - \frac{m\pi}{2} - \frac{\pi}{4})$$

The result given in (C-2) will be added to the truncated integral if the truncation was made on the Bessel function argument. The subroutine that

handles the evaluation of  $T_m(\alpha_t)$  is called ASYMP. In the case of the quasi-static method we have added a third criterion for the truncation of the integration and that depends on  $\alpha_0$  according to the method discussed in Section 4.2.

As we mentioned before numerical integration of individual segment along the real axis is performed by a modified quadrature Romberg scheme. The subroutine that performs the integration is called INTEGR, which is known to be a fast convergent one unless there is a discontinuity in the function within the integrated limits. INTEGR has been developed to integrate an array of functions. Thus all six integrations of the EM field components in the space region can be performed at once. The usual criteria of stopping the integration is by checking if either the absolute or relative error of the integration has reached the needed tolerance. More specifically in Figure 4, the integration routine calls two functions "GLES1" and "GGRT1" which they represent as the functions of the first and second integral in (34) respectively. SUBG gives the value of  $T(x)$  for any  $x$  as required in (34). SUBG calls two other subroutines, one is called "BEJY" which calculates the Bessel function  $J_0$  and  $J_1$ ; the other is "UV" which computes the values of the functions  $(E_w^\ell, H_w^\ell)$ ,  $\ell = 0, 1$  and  $w = x, y, z$ , listed in Table 2. Two other subroutines EVALUE and FINDZY are used in UV for the purpose of calculating the functions  $F_\ell(\alpha)$ ,  $\ell = 1, 2, 3$ , and  $N_0, K_0$ , etc., as given by (29) and (8) for a single slab respectively.

As we have noted earlier the usual method of integration becomes a time consuming one for large  $R$ . For such a case, we switch the program to a subroutine called ASMPT, based upon the asymptotic solution we derived in Section 4.1. For computing efficiently, this part of the program is further split up into a sky-wave region and a ground-wave region. This means we use a two term sky-wave solution where the observation is made away from the ground (subroutine LARGR) and a two-term ground wave solution as described in Section 4.1 (Subroutine FACTOR).

The subroutine QSTATC serves the purpose of finding the fields for a very small value of  $R$ , where  $R = k_0 R_{12}$  is the normalized distance from the dipole image to the observation point,  $R_{12} = [(z + h_0)^2 + r^2]^{\frac{1}{2}}$ . This subroutine follows exactly the procedure described under section 4.2 except Maxwell equations has to be used first to find the electromagnetic field components. The finite integration from 0 to  $\alpha_0$  for  $\Delta V_\ell$  ( $\ell = 1, 2, 3$ ) in (51) and (55), was performed by calling the subroutine "RESULT". However, analytical expression has been used to replace the integration from  $\alpha_0$  to infinity, i.e.  $V_\ell^{(2)}$  ( $\ell = 1, 2$ ) in (53) and  $V_3^{(3)}$  in (58). This analytical result has been built in a subroutine "CORREC" which is called from "RESULT" automatically when the integration has reached the upper limit  $\alpha_0$ . The leading terms, i.e.,  $V_\ell^{(1)}$  ( $\ell = 1, 2$ ) in (52) and  $V_3^{(1)}$  in (56), are calculated in QSTATC by calling two other subroutines "FIELD" and "QV3", the first of which calculates the free space Greens functions given in (24) and the second calculates the leading term of the cross coupling field  $V_3$  and is given by (56).

Finally, we should emphasize that the subroutines QSTATC and ASMPT are built to speed up the program. They are auxiliary routines to the main program which provides adequate approximate answers as an alternative to the exact but time consuming results available from the subroutine RESULT.

## APPENDIX C

### List of the Computer Program



```

SUBROUTINE DIPOLE(FREQN, EPSR, SIGMA, H1, H0, R, TH, PH, THP, NOROOT, A0,
1 ACCINT, TOTFLD, IFLAG)

```

```

C SUBROUTINE DIPOLE WAS DESIGNED TO FIND THE EM FIELD DUE TO AN
C ARBITRARY-ORIENTATED DIPOLE SOURCE ABOVE A TWO LAYER CONDUCTING
C EARTH. THE INPUTS TO THE PROGRAM ARE:
C FREQN=FREQUENCY OF OPERATION.
C (EPSR) AND (SIGMA) EACH OF WHICH SHOULD HAVE THE DIMENSION OF 3
C REPRESENTING THE DIELECTRIC CONSTANT AND CONDUCTIVITY (MHO/M)
C IN THE THREE MEDIA: AIR, SLAB REGION AND GROUND RESPECTIVELY.
C H1=SLAB WIDTH.
C H0=HEIGHT OF THE DIPOLE FROM THE SLAB SURFACE.
C R=THE DISTANCE OF THE DIPOLE IMAGE ABOVE A PERFECTLY CONDUCTING
C GROUND TO THE OBSERVATION POINT.  $R = \sqrt{(Z+H0)^2 + (SR)^2}$ ;
C WHERE SR=SMALL R, IS THE PROJECTION OF R INTO THE X-Y PLANE.
C TH=THETA IS THE IMAGE ANGLE (IN DEGREES) WHICH THE OBSERVATION
C POINT MAKES WITH THE Z-AXIS (REFER TO FIG-5 OF THE REPORT).
C PH=PHI IS THE OBSERVATION ANGLE (IN DEGREES) MEASURED IN THE X-Y
C PLANE.
C THP=THETA-PRIME IS THE ANGLE (IN DEGREES) THAT THE DIPOLE MAKES
C WITH THE VERTICAL AXIS. IF THP=0 THE DIPOLE IS VERTICAL AND
C IF THP=90 THEN THE DIPOLE IS HORIZONTAL.
C NOROOT=IS A LOGICAL STATEMENT WHEN IT IS TRUE NO SEARCH WILL BE
C MADE FOR THE POLES (PHYSICALLY, SURFACE WAVE MODES) IN THE
C SLAB REGION ALSO NO CALCULATION OF THE SOMMERFELD POLE WILL
C BE MADE IN THE HALF-SPACE CASE. IF (NOROOT) IS FALSE THEN
C A SEARCH FOR POLES WILL BE MADE.
C A0=IS THE POLE CLOSEST TO THE REAL-AXIS IN THE COMPLEX ALPHA-PLANE
C . IT SHOULD BE SPECIFIED ARBITRARILY IF THE ROOT FINDER IS NOT
C USED.
C ACCINT=IS THE ERROR TOLERANCE OF THE NUMERICAL INTEGRATION.
C TOTFLD=ARE THE CALCULATED VALUES OF ALL THE EM FIELD COMPONENTS.
C IT SHOULD BE DIMENSIONED AS TOTFLD(3,2). THE FIRST COLUMN
C ARE THE E-FIELD COMPONENTS (EX, EY AND EZ), AND THE SECOND
C COLUMN ARE THE H-FIELDS (HX, HY AND HZ).
C IFLAG=IS A LOGICAL STATEMENT WHICH IF IT IS TRUE QUASI-STATIC AND
C ASYMPTOTIC APPROX. WILL BE USED. IF (IFLAG) IS FALSE THEN
C USUAL NUMERICAL INTEGRATION METHOD WILL BE PERFORMED ON
C THE SO CALLED SOMMERFELD INTEGRALS.

```

```

COMMON /MAIN1/N(3), H, EPSR(3), RK0, K0, ZHM, TOL
COMMON /MAIN2/B, PHI, THETA, CT1, ST1, CP1, SP1, CP2, SP2
COMMON /MAIN3/SS(3), EE(3), HH, OM
COMMON /TYPE/IQIA
LOGICAL NOROOT, IFLAG
COMPLEX N, A0, J, FA, A
COMPLEX DI, DS, SOMFLD, TOTFLD, WAVE, PZS, PXS, PZI, PXI
REAL K0, MU0
DIMENSION A(5), SIGMA(3)
DIMENSION DI(3,2), DS(3,2), SOMFLD(3,2), PZS(3,2), PXS(3,2)
1, PZI(3,2), PXI(3,2), WAVE(3,2), TOTFLD(3,2)
TOL=ACCINT
J=(0., 1.)
PI=3.141592653
C=2.99793E+08
EPS0=8.854E-12 $ MU0=4.*PI*1.0E-07
EGZI=SQRT(MU0/EPS0)
CONV=PI/180.
OMEGA=2.*PI*FREQN
K0=OMEGA/C
H=H1*K0
FB=K0*K0/4./PI $ FA=J*EGZI*FB

```

```

DO 12 L=1,3
12 N(L)=CSQRT(EPSR(L)*(0.,1.)*SIGMA(L)/OMEGA/EPS0)
51 THETA=TH*CONV
  Z=R*COS(THETA)-H0 $ RO=R*SIN(THETA)
  ZH=Z+H0 $ ZHM=Z-H0
  B=ZH*K0 $ RK0=RO*K0
  PRINT 88,FREQN,(N(L),EPSR(L),SIGMA(L),L=1,3)
88 FORMAT (1H1*FREQUENCY=*E9.2,1X*C/S*/,1X*REFRACTIVE INDICES OF AIR,
1CEMENT AND EARTH RESPECTIVELY*/1X*N0=*F9.4,**J*F9.4,10X*EPSR0=*E8.
21,3X*SIGMA0=*E10.3/1X*N1=*F9.4,**J*F9.4,10X*EPSR1=*E8.1,3X*SIGMA1=
3*E10.3/,1X*N2=*F9.4,**J*F9.4,10X*EPSR2=*E8.1,3X*SIGMA2=*E10.3/)
  PRINT 14,Z,H0,H1,R,TH
14 FORMAT (1X,*Z=*E10.3,2X*M*,3X*OBSERVATION HEIGHT*/1X*H0=*E10.3,1X
1*M*,3X*DIPOLE HEIGHT*/1X*H1=*E10.3,1X*M*,3X*SLAB WIDTH*/1X*R=*E10.
23,2X*M*,3X*SOURCE TO OBSERVATION DISTANCE*/1X*THETA=*F5.1,1X*DEG*,
33X*ANGLE OF INCIDENCE*/)

C NO SEARCH FOR POLES WILL BE AVAILABLE WHEN NOROOT IS TRUE,THUS THE
C POLE LOCATION A0 SHOULD BE SPECIFIED .IF THESE POLES ARE FAR AWAY
C FROM THE REAL AXIS,ASSIGN ANY ARBITRARY POLE IN THE FIRST QUADRANT
C OF THE COMPLEX ALPHA-PLANE. THIS POLE SHOULD NOT BE CLOSE TO THE
C PATH OF INTEGRATION.

  IF (NOROOT) GO TO 22

C CHECK IF WE HAVE A TWO-LAYER EARTH MODEL,IF SO CALL RROOT ;
  IF (H.GT.1.0E-05.OR.H.LT.1.0E+05) GO TO 26

C IF NOT, WE HAVE A SINGLE LAYER EARTH .HENCE WE NEED TO FIND THE
C SOMMERFELD POLE;
  IF (H.LE.1.0E-05) A0=N(3)/CSQRT(N(3)*N(3)+1.)
  IF (H.GE.1.0E+05) A0=N(2)/CSQRT(N(2)*N(2)+1.)
  GO TO 22

C SUBROUTINE RROOT WAS DESIGNED TO FIND THE SURFACE WAVE MODES THAT
C EXIST IN A DIELECTRIC SLAB ABOVE A DISSIPATIVE EARTH.

26 DO 23 I=1,3
  EE(I)=EPSR(I)
23 SS(I)=SIGMA(I)
  OM=OMEGA $ HH=H
  CALL RROOT(A,A0)

C A0 WILL BE THE POLE CLOSEST TO THE PATH OF INTEGRATION.
C (A) WILL BE THE POLES THAT ARE FOUND . PLACES WHERE RROOT FAILS A
C MESSAGE WILL BE PRINTED AND THE ARBITRARY POLE (.95,.15) WILL BE
C ASSIGNED. UP TO 5 POLES WILL BE SEARCHED WITH THE EXISTING DIMENSION
C OF A(5). IF MORE EXIST ,THE DIMENSION OF (A) IN DIPOLE AND (ZERO)
C IN RROOT SHOULD BE INCREASED.

22 PHI=PH*CONV $ THETAP=THP*CONV
  CT1=COS(THETAP) $ ST1=SIN(THETAP)
  CP1=COS(PHI) $ SP1=SIN(PHI)
  CP2=COS(2.*PHI) $ SP2=SIN(2.*PHI)
  IF (IFLAG.LE.0) GO TO 165

C THE FOLLOWING THREE ROUTINES WILL BE USED FOR THE EVALUATION OF
C THE SOMMERFELD INTEGRALS
C (1) QUASI-STATIC APPROX.
C (2) NORMAL INTEGRATION ALONG THE REAL AXIS IN THE COMPLEX ALPHA-

```

```

C      PLANE .
C      (3) ASYMPTOTIC TECHNIQUES (USING STEEPEST DESCENT METHOD ).

      RN=R*K0
      IF (RN.GT.5.0E-02.OR.RN.LT.3.0E+01) GO TO 165
      IF (RN.GE.3.0E+01) GO TO 77

C      QUASI-STATIC APPROX. WILL BE PERFORMED .

      IQIA=1
      CALL QSTATC(A0,WAVE,3,2,IQIA)
      GO TO 33

C      ASYMPTOTIC APPROX. WILL BE PERFORMED .

77 IQIA=3
   CALL ASMPT(A0,THETA,WAVE,3,2)
   GO TO 33

C      IN HERE, JUST REGULAR INTEGRATION METHOD WILL BE USED TO FIND THE
C      SOMMERFELD INTEGRALS .

165 CALL FIELD(DS,K0,ZHM,R0,PZS,PXS,3,2)
   CALL FIELD(DI,K0,ZH,R0,PZI,PXI,3,2)
   IQIA=2
   CALL RESULT(A0,SOMFLD,3,2,IQIA)
   DO 6 JJ=1,2
   DO 6 II=1,3
6  WAVE(II,JJ)=DS(II,JJ)-DI(II,JJ)+SOMFLD(II,JJ)
33 DO 2 JJ=1,2
   DO 4 II=1,3
   IF (JJ.EQ.2) GO TO 56
   TOTFLD(II,JJ)=FA*WAVE(II,JJ)
   GO TO 4
56 TOTFLD(II,JJ)=FB*WAVE(II,JJ)
4  CONTINUE
2  CONTINUE
   RETURN
   END

```

SUBROUTINE FIELD(D,K,ZH0,RO,X,Y,I,M)

C THIS SUBROUTINE EVALUATES ALL THE ELECTROMAGNETIC FIELD COMPONENTS  
 C DUE TO AN ELECTRIC VECTOR POTENTIAL OF THE FORM  $G_{11} = \exp(J \cdot R_{11}) / R_{11}$   
 C OR  $G_{12} = \exp(J \cdot R_{12}) / R_{12}$  WHERE  $R_{11} = \sqrt{(Z-H_0)^2 + RHO^2}$  AND  
 C  $R_{12} = \sqrt{(Z+H_0)^2 + RHO^2}$ . Z, H0 AND RHO ARE NORMALIZED TO THE FREE  
 C SPACE WAVELENGTH  $K_0$ . THE INPUTS ARE ;  
 C (1) K IS FREE SPACE WAVELENGTH.  
 C (2) RO IS A RADIAL DISTANCE.  
 C (3) ZH0 REPRESENTS THE NON-NORMALIZED DISTANCE (Z-H0) OR (Z+H0).  
 C THE OUTPUTS ARE ;  
 C (1) D REPRESENTS THE FIELD DUE TO  $G_{11}$  OR  $G_{12}$ .  
 C (2) X AND Y REPRESENT THE FIELD DUE TO A VERTICAL AND A HORIZONTAL  
 C DIPOLE RESPECTIVELY.

COMMON /MAIN2/BB,P,T,CT,ST

COMPLEX G11,J,F,D,X,Y

REAL K

DIMENSION X(3,2),Y(3,2),D(3,2)

J=(0.,1.)

R=SQRT(RO\*RO+ZH0\*ZH0)

A=1./(K\*R)

G11= CEXP(J\*K\*R)\*A

B=A\*A

XR=RO\*COS(P)/R \$ YR=RO\*SIN(P)/R

ZR=ZH0/R

F=1.+3.\*J\*A-3.\*B

X(1,1)=-F\*XR\*ZR\*G11\*CT \$ Y(1,1)=-F\*XR\*XR-1.-J\*A+B)\*G11\*ST  
 X(2,1)=-F\*YR\*G11\*ZR\*CT \$ Y(2,1)=-F\*YR\*G11\*XR\*ST  
 X(3,1)=-F\*ZR\*ZR-1.-J\*A+B)\*G11\*CT \$ Y(3,1)=-F\*XR\*ZR\*G11\*ST  
 X(1,2)=(J-A)\*YR\*G11\*CT \$ Y(1,2)=(0.,0.)  
 X(2,2)=(A-J)\*G11\*XR\*CT \$ Y(2,2)=(J-A)\*G11\*ZR\*ST  
 X(3,2)=(0.,0.) \$ Y(3,2)=(A-J)\*YR\*G11\*ST

DO 22 JJ=1,2

DO 22 II=1,3

22 D(II,JJ)=X(II,JJ)+Y(II,JJ)

RETURN

END

```
SUBROUTINE LARGR(THETA,FLD,II,MM)
```

```
C THIS SUBROUTINE EVALUATES THE EM FIELD COMPONENTS IN THE AIR REGION
C ASSUMING A PLANE WAVE INCIDENCE ON THE AIR AND SLAB INTERFACE (SKY-
C WAVE ASYMPTOTIC APPROXIMATION OF THE SOMMERFELD INTEGRALS).THE INPUT
C IS THETA=ARCTAN(RO/(Z+H0)).THE OUTPUT IS FLD. II AND MM ARE VARIABLE
C DIMENSIONS.
```

```
COMMON /MAIN1/N(3),H,E(3),RK,K0,ZHM
COMMON /MAIN2/B,P,TP,CT,ST,CP
COMMON /ZYY/YZ(3)
COMMON /FUV/AL,GG0,GG1,GG2
REAL K0
COMPLEX GG0,GG1,GG2,PZS,PXS,PZI,PXI,YZ,REFL1,REFL2
1,DI,DS,FLD,N,J
DIMENSION DI(3,2),DS(3,2),FLD(II,MM),PZS(3,2),PXS(3,2)
1,PZI(3,2),PXI(3,2)
J=(0.,1.)
AL=SIN(THETA)      $ GG0=-J*COS(THETA)
GG1=CSQRT(AL*AL-N(2)*N(2))
GG2=CSQRT(AL*AL-N(3)*N(3))
ZH=B/K0            $ RO=RK/K0
```

```
CALL FINDZY
```

```
C PARALLEL POLARIZATION REFLECTION COEFFICIENT.
```

```
REFL1=(GG0-YZ(1))/(GG0+YZ(1))
```

```
C PERPENDICULAR POLARIZATION REFLECTION COEFFICIENT.
```

```
REFL2=(GG0-YZ(2))/(GG0+YZ(2))
```

```
C EM FIELD DUE TO G11=EXP(I*R11)/R11
```

```
CALL FIELD(DS,K0,ZHM,RO,PZS,PXS,II,MM)
```

```
C EM FIELD DUE TO G12=EXP(I*R12)/R12
```

```
CALL FIELD(DI,K0,ZH,RO,PZI,PXI,II,MM)
```

```
DO 5 M=1,MM
```

```
DO 5 I=1,II
```

```
5 FLD(I,M)=PZS(I,M)+REFL1*PZI(I,M)+PXS(I,M)+
1(-REFL1*CP+REFL2*(1.-CP))*PXI(I,M)
```

```
RETURN
```

```
END
```

```

SUBROUTINE RESULT(ALPHA0,VALUE,KK,LL,IQ)
C THIS SUBROUTINE CALCULATES THE SOMMERFELD INTEGRALS GIVEN IN EQ.
C (30) OF THE REPORT, HOWEVER WHEN IQ=1, THEN IT CALCULATES THE
C INTEGRALS OF (51) AND (55).
C INPUT E(ALPHA0) IS POLE LOCATION IN COMPLEX ALPHA PLANE.
C OUTPUT E(VALUE), KK AND LL ARE VARIABLE DIMENSIONS.

```

```

COMMON /MAIN1/N(3),H,EPSR(3),RK,FK,ZM,TOLRNS
COMMON /MAIN2/B,PHI,THETAP
COMPLEX N,ALPHA0,VALUE
COMPLEX SUM,SAVE
DIMENSION SUM(3,2),SAVE(3,2),VALUE(KK,LL)
EXTERNAL GLES1,GGRT1
LOGICAL TEST
PI=3.141592653
NI=2048
EE=1.0E-06

```

```

C CRITERIA FOR THE SUBDIVISION OF THE INTEGRATION.

```

```

CR=6.0/(RK+EE) $ CZ=3.0/(B+EE) $ CH=1.0/(H+EE)
FACT1 =AMIN1(CR,CZ,CH)

```

```

C CRITERION FOR UPPER LIMIT TRUNCATION IN THE QUASI-STATIC CASE
C SEE SECTION 4.2 OF THE REPORT.

```

```

EN=CABS(N(2)) $ EN1=10.*EN
HC=SQRT(50.0*CH*CH+EN*EN) $ CCH=AMAX1(HC,EN1)
DO 1 LI=1,LL
DO 1 KI=1,KK
1 SAVE(KI,LI)=(0.,0.)
ACC=TOLRNS

```

```

C HERE, WE DETERMINE THE CIRCLE OF INFLUENCE DUE TO THE POLE MOTION
C AS DISCUSSED IN SECTION 3.

```

```

AR=REAL(ALPHA0) $ AI=AIMAG(ALPHA0)
RR=SQRT((AR-1.)**2+AI**2)
IF (AR.GT.1.) GO TO 33
DIF=1.-4.*RR $ ADD=1.+4.*RR
GO TO 36
33 DIF=AR-4.*RR $ ADD=AR+4.*RR
36 IF (DIF) 15,15,16

```

```

C THE POLE HAS NO INFLUENCE ON THE PATH OF INTEGRATION, THUS THE
C PATH WILL BE SUBDIVIDED AS GIVEN BY EQ. (34) OF THE REPORT

```

```

15 T1=0. $ T2=1.
IJ=1 $ GO TO 27
16 IF (DIF.LE.1.) GO TO 105

```

```

C THE POLE HAS AN INFLUENCE BEYOND THE BRANCH POINT AT ALPHA=1.

```

```

EPS1=SQRT(DIF*DIF-1.) $ EPS2=SQRT(ADD*ADD-1.)
T1=0. $ T2=1.
IJ=3 $ II=1
EPS=EPS1
RZ=AMIN1(CR,CZ)
IF (EPS1.GE.RZ) EPS=RZ
GO TO 27

```

```

C HERE, THE POLE HAS AN INFLUENCE IN THE REGION FOR ALPHA BETWEEN
C 0 AND 1.

```

```

105 EPS1=SQRT(1.-DIF*DIF) $ EPS=SQRT(ADD*ADD-1.)
T1=0. $ T2=EPS1
IJ=2 $ II=0
EPS2=AMIN1(EPS,CR,CZ)

```

C FIRST INTEGRATION FOR ALPHA BETWEEN 0 AND 1 AS GIVEN IN THE FIRST  
C TERM OF (34). GLESI REPRESENTS THE FUNCTIONS TO BE INTEGRATED IN  
C THIS REGION.

```

27 CALL INTEGR(T1,T2,ACC,NI,GLESI,SUM,KK,LL,X,XREL,NUSED,TEST)
   DO 3 LI=1,LL
   DO 3 KI=1,KK
3  SAVE(KI,LI)=SAVE(KI,LI)+(A.,1.)*SUM(KI,LI)
   IF (TEST) PRINT 200,X,XREL,T1,T2,((SUM(KI,LI),SAVE(KI,LI)
1,KI=1,KK),LI=1,LL),NUSED
   IF (IJ.EQ.1) GO TO 35
   IF (II.EQ.1) GO TO 30
   T1=T2      $      T2=1.0
   II=1      $      ACC=TOLRNS      $      GO TO 27
30 NI=1024    $      IF (IJ.EQ.3) GO TO 50
   T1=0.      $      T2=EPS2      $      II=2
   ACC=TOLRNS/3.0
   GO TO 40
90 T1=0.      $      T2=EPS1      $      II=1
   GO TO 40
45 T1=T2      $      T2=EPS2
   ACC=TOLRNS      $      II=2
   GO TO 40
35 T1=0.      $      T2=T2+FACTI

```

\*C SECOND INTEGRATION IS FOR THE REGION BEYOND THE BRANCH POINT AT  
C ALPHA=1. GGRTI REPRESENTS THE FUNCTIONS TO BE INTEGRATED.

```

40 CALL INTEGR(T1,T2,ACC,NI,GGRTI,SUM,KK,LL,X,XREL,NUSED,TEST)
   DO 5 LI=1,LL
   DO 5 KI=1,KK
5  SAVE(KI,LI)=SAVE(KI,LI)+SUM(KI,LI)
   IF (TEST) PRINT 200,X,XREL,T1,T2,((SUM(KI,LI),SAVE(KI,LI)
1,KI=1,KK),LI=1,LL),NUSED
   IF (IJ.EQ.3.AND.II.EQ.1) GO TO 45
   ACC=TOLRNS/3.0
   A=SQRT(1.+T2*T2)
   FACT2=A*RK

```

C CHECK IF THE ARGUMENT OF THE BESSEL FUNCTION HAD REACHED THE VALUE  
C OF 50. IF SO, USE ASYMPTOTIC APPROX. FOR THE REGION BEYOND THIS  
C POINT AS DESCRIBED IN APPENDIX-C EQ. C-2 OF THE REPORT.

```
IF (FACT2.GE.50.0.AND.T2.GE.EPS) GO TO 39
```

C CHECK IF WE HAVE A QUASI-STATIC CASE, IF SO, PERFORM THE INTEGRATION  
C GIVEN IN EQ. (51) AND (55) AND THEN ADD THE CORRECTION TERMS  
C WHICH REPRESENTS ANALYTICAL APPROX. OF THE INTEGR. FROM ALPHAT  
C TO INFINITY AS DESCRIBED IN APPENDICES A AND B.

```
IF (IQ.EQ.1.AND.T2.GE.CCH) GO TO 115
202 TT=B*T2
```

C CHECK IF THE EXPONENTIAL FUNCTION  $\exp(-\text{GAMMA0} \cdot B)$  HAS REACHED  
C THE VALUE OF  $\exp(-12)$ . IF SO, STOP THE INTEGRATION.

```

IF (TT.GT.12.) GO TO 100
T1=T2      $      T2=T2+FACT1
GO TO 40
115 CALL CORREC(A,SUM,KK,LL)
GO TO 110
39 CALL ASYMP(A,SUM,KK,LL)
110 DO 7 LI=1,LL
DO 7 KI=1,KK
7  SAVE(KI,LI)=SAVE(KI,LI)+SUM(KI,LI)
100 DO 9 LI=1,LL
DO 9 KI=1,KK
9  VALUE(KI,LI)=SAVE(KI,LI)
200 FORMAT (/5X,*ABS.,REL. ERPS.==2(2XE13.6),3X*LL=*E13.5,3X*UL=*E13.5
1/1X*SUM MATRIX*/1X,6(2E13.5,5X,2E13.5/),2X*NUMB. OF ITER.=*I6/)
RETURN
END

```

```

      SUBROUTINE INTEGR (A,B,EPS,NSTEP,F,VALUE,L,M,X,XRELTV,K,G)
C   THIS SUBROUTINE PERFORMS AN (L,M) ARRAY OF COMPLEX FUCTIONS
C   INTEGRATION USING MODIFIED ROMBERG TECHNIQUE.
C   AELOWER LIMIT , BEUPPER LIMIT OF THE INTEGRATION
C   EPSEREQUIRED TOLERANCE.
C   NSTEP= MAX. NUMBER OF ITERATION TO BE USED FOR PERFORMIG THE
C   INTEGRATION.
C   FE A SUBROUTINE HAS AN (L,M) ARRAY OF FUNCTIONS (INTEGRANDS).
C   VALUE= OUTPUT OF THE INTEGRATION ,(L,M) ARRAYS OF VALUES.
C   XE RETURNED ABSOLUTE ERROR .      XRELTVE RETURNED RELATIVE ERROR.
C   K=NUMBER OF ITERATION USED IN PERFORMING THE INTEGRATION.
C   GELOGICAL STATEMENT IF IT IS FALSE ,THEN ,THE INTEGRATION WAS
C   PERFORMED WITHIN THE REQUIRED TOLERANCE (EPS) AND THE ITERATION
C   SIZE (NSTEP). OTERWISE IF IT IS TRUE ,THEN X ,XRELTV AND K
C   WILL BE RETURNED.

      COMPLEX FCNA,FCNB,FCNXI,T,SUM,QX1,QX2,VALUE,Q
      DIMENSION SUM(3,2),FCNA(3,2),FCNB(3,2),T(3,2),FCNXI(3,2),
1QX1(3,2),QX2(3,2),VALUE(L,M),Q(16,3,2)
      LOGICAL G
      H=B-A
      CALL F(A,FCNA,L,M) $ CALL F(B,FCNB,L,M)
      DO 67 MJ=1,M
      DO 67 LJ=1,L
67  T(LJ,MJ)=(FCNA(LJ,MJ)+FCNB(LJ,MJ))*H/2.
      NX=1
      N=1
1  K=2**N
      H=H/2.
      DO 22 MJ=1,M
      DO 22 LJ=1,L
22  SUM(LJ,MJ)=(0.,0.)
      DO 2 I=1,NX
      XI=2.*FLOAT(I)-1.
      XA=A+XI*H
      CALL F(XA,FCNXI,L,M)
      DO 24 MJ=1,M
      DO 24 LJ=1,L
24  SUM(LJ,MJ)=SUM(LJ,MJ)+FCNXI(LJ,MJ)
2  CONTINUE
      DO 26 MJ=1,M
      DO 26 LJ=1,L
      T(LJ,MJ)=T(LJ,MJ)/2.+H*SUM(LJ,MJ)
26  Q(N,LJ,MJ)=(T(LJ,MJ)+H*SUM(LJ,MJ))*2./3.
      IF (N-2) 10,3,3
3  F=4.
      DO 4 J=2,N
      I=N+1-J
      F=F*4.
      DO 27 MJ=1,M
      DO 27 LJ=1,L
27  Q(I,LJ,MJ)=Q(I+1,LJ,MJ)+(Q(I+1,LJ,MJ)-Q(I,LJ,MJ))/(F-1.)
4  CONTINUE
      IF (N-3) 9,5,5
5  X=0. $ XRELTV=0.
      DO 29 MJ=1,M
      DO 29 LJ=1,L
      XREAL=ABS(REAL(Q(1,LJ,MJ)-QX2(LJ,MJ)))+ABS(REAL(QX2(LJ,MJ)
1-QX1(LJ,MJ)))
      XIMAG=ABS(AIMAG(Q(1,LJ,MJ)-QX2(LJ,MJ)))+ABS(AIMAG(QX2(LJ,MJ)
1-QX1(LJ,MJ)))
      CR=CABS(Q(1,LJ,MJ))
      IF (CR.EQ.0.0) GO TO 33
      XR=AMAX1(XREAL,XIMAG)/CR $ GO TO 107

```



```

33 XR=0.0
107 XRELTV=AMAX1(XR,XRELTV)
29 X=AMAX1(X,XREAL,XIMAG)
   COMPA=X-3.*EPS
   COMPR=XRELTV-3.*EPS
   IF (COMPA.LE.0.0.OR.COMPR.LE.0.0) 11,8
8 IF (NSTEP-K) 11,11,9
9 DO 37 MJ=1,M
  DO 37 LJ=1,L
37 QX1(LJ,MJ)=QX2(LJ,MJ)
10 DO 39 MJ=1,M
  DO 39 LJ=1,L
39 QX2(LJ,MJ)=Q(1,LJ,MJ)
12 NX=NX+2
   N=N+1
   GO TO 1
11 DO 41 MJ=1,M
  DO 41 LJ=1,L
41 VALUE(LJ,MJ)=Q(1,LJ,MJ)
   G=NSTEP.LT.K
   RETURN
   END

```

#### SUBROUTINE GLESL(T,GL,I,J)

C HERE, WE EVALUATE THE FIRST INTEGRAND OF EQ. (34) OF THE REPORT.  
 C THE REGION IS FOR ALPHA BETWEEN 0 AND 1.  
 C T IS THE INPUT .OUTPUT=GG IS AN ARRAY OF (I,J) FUCTIONS.

```

COMPLEX G,GL
DIMENSION GL(I,J),G(3,2)
X=SQRT(1.-T*T)
CALL SUBG(X,G,I,J)
DO 10 N=1,J
DO 10 M=1,I
10 GL(M,N)=G(M,N)
RETURN
END

```

#### SUBROUTINE GGRT1(T,GG,I,J)

C THIS SUBROUTINE EVALUATES THE SECOND INTEGRAND OF EQ. (34) OF THE  
 C REPORT. THIS REGION IS FOR ALPHA GREATER THAN 1.  
 C T IS THE INPUT .OUTPUT=GG IS AN ARRAY OF (I,J) FUCTIONS.

```

COMPLEX G,GG
DIMENSION GG(I,J),G(3,2)
X=SQRT(1.+T*T)
CALL SUBG(X,G,I,J)
DO 10 N=1,J
DO 10 M=1,I
10 GG(M,N)=G(M,N)
RETURN
END

```

SUBROUTINE SUBG(ALPHA,G,II,JJ)

C HERE, WE CALCULATES THE FUNCTIONS GIVEN IN EQ. (30) OF THE REPORT.  
C INPUT=ALPHA , OUTPUT=G IS AN ARRAY OF (II,JJ) FUCTIONS.

```
COMMON /MAIN1/N(3),H,EPS(3),RK0
COMMON /MAIN2/B
DIMENSION BESSJ(2),BESSY(2),Y(3,2),Z(3,2),G(II,JJ)
COMPLEX N,CX,GAMA0,Y,Z,J0,J1,G
X=ALPHA
IF (X-1.0) 10,20,30
10 GAMA0=(0.,-1.)*SQRT(1.-X*X) $ GO TO 40
20 GAMA0=(0.,0.) $ GO TO 40
30 GAMA0=SQRT(X*X-1.)
40 RA=X*RK0
CX=CEXP(-GAMA0*B)
```

C A CALL WILL BE MADE TO SUBROUTINE (UV) TO EVALUATE THE FUNCTIONS  
C LISTED IN TABLE-2 OF THE REPORT.

CALL UV(X,GAMA0,Y,Z,II,JJ)

C THE OTHER CALL WILL BE MADE TO BEJY TO EVALUATE THE BESSEL  
C FUCTIONS J0 AND J1 .

```
CALL BEJY(RA,BESSJ,BESSY,2,0)
J0=BESSJ(1) $ J1=BESSJ(2)
DO 22 JM=1,JJ
DO 22 IM=1,II
22 G(IM,JM)=CX*(Y(IM,JM)*J0+Z(IM,JM)*J1)
RETURN
END
```

SUBROUTINE UV(ALPHA,G0,U,V,IJ,IK)

C SUBROUTINE UV CALCULATES THE FUNCTIONS LISTED IN TABLE-2. INPUTS ARE:  
C (1) ALPHA, WHICH IS REAL SINCE THE INTEGRATION IS ALONG THE REAL-  
C AXIS IN THE COMPLEX ALPHA-PLANE.  
C (2) G0=SQRT((ALPHA)\*\*2-1) , HERE G0 IS COMPLEX AND THE CHOICE OF  
C THE BRANCH CUT IS G0=-J\*SQRT(1-(ALPHA)\*\*2) FOR ALPHA<1.  
C THE OUTPUTS ARE :  
C (1) U AND V REPRESENT THE VALUES OF THE LEFT AND THE RIGHT COLUMNS  
C OF TABLE-2 RESPECTIVELY. IJ AND IK ARE VARIABLE DIMENSIONS.

```
COMMON /MAIN1/N(3),H,EPSR(3),RK0
COMMON /MAIN2/B,P,T,CT,ST,CP,SP,CP2,SP2
COMMON /FINDF/F(3)
COMMON /FUV/A,GAMA0,G1,G2
COMPLEX N,G0,G1,G2,GAMA0
COMPLEX F,FG,U,V
DIMENSION U(3,2),V(3,2)
A=ALPHA
GAMA0=G0
G1=CSQRT(A*A-N(2)*N(2))
G2=CSQRT(A*A-N(3)*N(3))
RK=RK0
A2=A*A
```

C FIND THE VALUES OF  $(G0*F1)$ ,  $(G0*F2)$  AND  $(G0*F3)$ , WHERE  $F1$ ,  $F2$  AND  $F3$   
 C ARE GIVEN IN EQ. (29) OF THE REPORT.

CALL FVALUE

FG=F(2)-G0\*F(3)

U(1,1)=(F(2)-FG\*A2\*CP\*CP)\*ST  
 V(1,1)=(FG\*CP2\*ST/RK+G0\*F(1)\*CP\*CT)\*A  
 U(2,1)=-A2\*FG\*SP2\*ST/2.  
 V(2,1)=A\*(FG\*SP2\*ST/RK+G0\*F(1)\*SP\*CT)  
 U(3,1)=A2\*F(1)\*CT  
 V(3,1)=A\*(G0\*FG-F(3))\*CP\*ST  
 U(1,2)=-A2\*F(3)\*SP2\*ST/2.  
 V(1,2)=A\*(F(3)\*SP2\*ST/RK-F(1)\*SP\*CT)  
 U(2,2)=(-G0\*F(2)+A2\*F(3)\*CP\*CP)\*ST  
 V(2,2)=A\*(-F(3)\*CP2\*ST/RK+F(1)\*CP\*CT)  
 U(3,2)=(0.,0.)  
 V(3,2)=A\*F(2)\*SP\*ST

RETURN  
 END

SUBROUTINE FVALUE

C THIS SUBROUTINE EVALUATES DIFFERENT TYPES OF FUNCTIONS DEPENDING  
 C ON THE VALUE OF (I) IN THE COMMON BLOCK (TYPE). (I) DETERMINE THE  
 C FOLLOWING CASES  
 C (1) IF I=1, THEN ,IT CALCULATES THE QUASI-STATIC FUNCTIONS LISTED  
 C IN EQ. (51) AND (55) OF THE REPORT.  
 C (2) FOR I=2, FVALUE CALCULATES  $(G0*F1)$ ,  $(G0*F2)$  AND  $(G0*F3)$  WHERE  
 C  $F1$ ,  $F2$ , AND  $F3$  ARE GIVEN IN (29) OF THE REPORT AND  
 C  $G0=\text{SQRT}((\text{ALPHA})^{**2}-1.)$ .  
 C (3) WHEN I=3, (FVALUE) CALCULATES  $F1$ ,  $F2$  AND  $F3$  AND THEY WILL BE  
 C USED IN THE ASYMPTOTIC FORM FOR THE EM FIELD COMPONENTS.  
 C THE OUTPUT OF THIS SUBROUTINE IS THE COMMON BLOCK /FINDF/.  
 C THE INPUTS ARE THRU THE FOLLOWING COMMON BLOCKS  
 C /MAIN1/ N(3) AND EPSR(3) ARE THE REFRACTIVE INDICES AND RELATIVE  
 C DIELECTRIC CONSTANTS OF THE THREE MEDIA.  
 C /FUV/ (A) =(ALPHA) , (G0)=(GAMMA0) , (G1)=(GAMMA1) , (G2)=(GAMMA2).  
 C H IS THE NORMALIZED SLAB WIDTH.  
 C /ZYY/ ZY(1) =(K0) , ZY(2)=(N0) , ZY(3)=1/w1 AS GIVEN IN EQ. (8).  
 C (9) AND (11) OF THE REPORT.

COMMON /MAIN1/N(3),H,EPSR(3)  
 COMMON /FINDF/F(3)  
 COMMON /FUV/A,G0,G1,G2  
 COMMON /ZYY/ZY(3)  
 COMMON /TYPE/I  
 COMPLEX F,ZY,LAMDA1,LAMDA2  
 COMPLEX N,G0,G1,G2,E1,E2  
 CALL FINDZY  
 E1=N(2)\*N(2) \$ E2=N(3)\*N(3)  
 LAMDA2=1./E2-1./E1  
 LAMDA1=LAMDA2\*ZY(3)-1.+1./E1

F(1)=2.\*G0/(G0+ZY(1))  
 F(2)=2.\*G0/(G0+ZY(2))  
 F(3)=LAMDA1\*(F(2)-F(1))/(ZY(2)-ZY(1))

```

      IF (I-2) 10,20,30
10  F(1)=F(1)-2.*E1/(E1+1.)
    F(2)=F(2)-1.
    F(3)=F(3)-(E1-1.)*G0/((E1+1.)*G1**2)

    RETURN
30  F(1)= 2./(G0+ZY(1))
    F(2)= 2./(G0+ZY(2))
    F(3)=LAMDAL*(F(2)-F(1))/(ZY(2)-ZY(1))

20  RETURN
    END

```

# SUBROUTINE FINDZY

C THIS SUBROUTINE CALCULATES THE VALUES OF K0,N0, AND 1/W1 AS GIVEN IN  
C (8),(9) AND (11) OF THE REPORT . THE OUTPUT IS THRU THE COMMON  
C BLOCK /ZYY/

```

COMMON /MAIN1/N(3),H,EPS(3)
COMMON /FUV/A,G0,G1,G2
COMMON /ZYY/ZY(3)
COMPLEX N,G0,G1,G2,Z2,Y2,Z,ZY,T,E1,E2,CT,DENY,DENZ
E1=N(2)*N(2)      $      E2=N(3)*N(3)
Z=(0.,1.)*G1      $      T=Z*H
Y2=G2              $      Z2=Y2/E2
ZI=AIMAG(2.*T)
IF (ABS(ZI).GE.60.0) GO TO 10
CT=CSIN(T)/CCOS(T)
DENY=Z+Y2*CT      $      DENZ=Z/E1+Z2*CT
ZY(3)=Z*Z/(E1*DENZ*DENY*0.5*(1.+CCOS(2.*T)))
20 ZY(1)=(Z/E1)*(Z2-Z*CT/E1)/DENZ
   ZY(2)=Z*(Y2-Z*CT)/DENY
   RETURN
10 ZY(3)=(0.,0.)    $      CT=(0.,1.)
   DENY=Z+Y2*CT     $      DENZ=Z/E1+Z2*CT
   GO TO 20
   END

```

```

SUBROUTINE BEJY(X,BJ,BY,M,N)
  DIMENSION BJ(2),BY(2)

```

```

C  BEJY CALCULATES THE BESSEL FUNCTIONS J0,J1,Y0 AND Y1.INPUTS ARE:
C  (1) X WHICH IS THE ARGUMENT OF THE BESSEL FUNCTIONS.
C  (2) M AND N DETERMINES WHICH TYPE OF BESSEL FUNCTIONS IS NEEDED.
C  EXAMPLE WHEN (M,N)=(1,0) J0 WILL BE CALCULATED.
C  THE OUTPUTS ARE BJ AND BY REPRESENTING BESSEL AND NEUMANN FUNCTION
C  RESPECTIVELY.

      T=X/3.
      Y=T*T
      Z=3./X
      IF(X.GE.3.) GO TO 10
      BJ(1)=1.-Y*(2.2499997-Y*(1.2656208-Y*(.3163866-Y*(.0444479-
1Y*(.0039444-Y*.0002100))))))
      GO TO 11
10  W=SQRT(X)
      AF=.79788456-Z*(.00000077+Z*(.00552740+Z*(.00009512-Z*(.00137237
1-Z*(.00072805-Z*.00014476))))))
      THETA=X-.78539816-Z*(.04166397+Z*(.00003954-Z*(.00262573
1-Z*(.00054125+Z*(.00029333-Z*.00013558))))))
      BJ(1)=AF*COS(THETA)/W
11  IF(N.GT.0) GO TO 20
      IF(M.EQ.2) GO TO 40
      RETURN
20  IF(X.GE.3.) GO TO 30
      BY(1)=2./3.14159265*ALOG(X/2.)*BJ(1)+.36746691+Y*(.60559366-
1Y*(.74350384-Y*(.25300117-Y*(.04261214-Y*(.00427916-Y*.00024846)))
2))
      GO TO 31
30  BY(1)=AF*SIN(THETA)/W
31  IF(M.EQ.2) GO TO 40
      RETURN
40  IF(X.GE.3.) GO TO 50
      BJ(2)=0.5-Y*(.56249985-Y*(.21093573-Y*(.03954289-Y*(.00443319
1-Y*(.00031761-Y*.00001109))))))
      BJ(2)=BJ(2)*X
      GO TO 51
50  AF=.79788456+Z*(.00000156+Z*(.01659667+Z*(.00017105-Z*(.00249511
1-Z*(.00113653-Z*.00020033))))))
      THETA=X-2.35619449+Z*(.12499612+Z*(.00005650-Z*(.00637879
1-Z*(.00074348+Z*(.00079824-Z*.00029166))))))
      BJ(2)=AF*COS(THETA)/W
51  IF(N.EQ.2) GO TO 60
      RETURN
60  IF(X.GE.3.) GO TO 70
      BY(2)=2./3.14159265*X*ALOG(X/2.)*BJ(2)+.6366198+Y*(.2212091+Y*(
12.1682709-Y*(1.3164827-Y*(.2123951-Y*(.0400976-Y*.0027873))))))
      BY(2)=BY(2)/X
      GO TO 71
70  BY(2)=AF*SIN(THETA)/W
71  RETURN
      END

```

## SUBROUTINE ASYMP(X,Z,II,JJ)

```

C THIS SUBROUTINE CALCULATES THE TRUNCATED INTEGRALS FROM ALPHAT
C TO INFINITY AS SHOWN IN C-2 OF THE REPORT. INPUT (X) REPRESENTS
C THE LOWER LIMIT OF THE INTEGRAL. (Z) IS THE OUTPUT WHICH IS THE
C CALCULATED ANALYTICAL APPROX. ,II AND JJ ARE JUST VARIABLE DIMENS.

COMMON /MAIN1/N(3),H,EPS(3),RK
COMMON /MAIN2/B
COMPLEX F,GG,FF,YY,ZZ,YX,ZX,N,GAMA0,Z,G1,G2,DYZ,DFY,DFZ,PF,RF
DIMENSION YY(3,2),ZZ(3,2),YX(3,2),ZX(3,2),G1(3,2),G2(3,2),Z(II,JJ)
1,PF(3,3,2),RF(3,3,2),DFY(3,2),DFZ(3,2)
FF(X,GG,RR)=XX*SQRT(2./(3.141592653*RR))*CEXP(-GG*B)/GG
PI=3.141592653
GAMA0=SQRT(X*X-1.)
RA=X*RK      S   PP=RA-PI/4.
CALL UV(X,GAMA0,YY,ZZ,II,JJ)
SI=SIN(PP)   S   CI=COS(PP)
F=FF(X,GAMA0,RA)
DO 10 J=1,JJ
DO 10 I=1,II
PF(1,I,J)=F*YY(I,J)      S   RF(1,I,J)=F*ZZ(I,J)
10 G1(I,J)=(-PF(1,I,J)*(SI-CI/(8.*RA))+RF(1,I,J)*(CI-3.*SI/(8.*RA)))
1/RK
D=1.0E-04
DO 39 M=2,3
XD=X+(M-1)*D      S   RD=XD*RK
GAMA0=SQRT(XD*XD-1.)
CALL UV(XD,GAMA0,YX,ZX,II,JJ)
DYZ=FF(XD,GAMA0,RD)
DO 37 J=1,JJ
DO 37 I=1,II
PF(M,I,J)=DYZ*YX(I,J)
37 RF(M,I,J)=DYZ*ZX(I,J)
39 CONTINUE
R2=RK*RK
DO 20 J=1,JJ
DO 20 I=1,II
DFY(I,J)=(-3.*PF(1,I,J)+4.*PF(2,I,J)-PF(3,I,J))/(2.*D)
DFZ(I,J)=(-3.*RF(1,I,J)+4.*RF(2,I,J)-RF(3,I,J))/(2.*D)
G2(I,J)=(-CI*DFY(I,J)-SI*DFZ(I,J))/R2
20 Z(I,J)=G1(I,J)+G2(I,J)
RETURN
END

```

## SUBROUTINE QSTATC(A0,TOTL,II,JJ,IQ)

C QUASI-STATIC APPROX. WILL BE EVALUATED IN THIS SUBROUTINE.  
 C (A0) REPRESENTS THE POLE LOCATION IN THE COMPLEX ALPHA-PLANE.  
 C (TOTL) IS THE OUTPUT OF THIS SUBROUTINE WHICH IS THE CALCULATED  
 C ARRAY OF FIELD COMPONENTS. II AND JJ ARE VARIABLE DIMENSIONS.  
 C (IQ) IS A FLAG AND IT SHOULD BE 1 IF QUASI-STATIC APPROX. IS NEEDED.

```
COMMON /MAIN1/N(3),H,E(3),RK,K0,ZHM
COMMON /MAIN2/B,PHI,T,CT,ST
REAL K0
COMPLEX N,DS,DI,PZS,PZI,PXS,PXI,Q,TOTL,SOM,C,A0,E1
DIMENSION DS(3,2),DI(3,2),PZS(3,2),PZI(3,2),PXS(3,2),PXI(3,2)
1,TOTL(II,JJ),SOM(3,2),Q(3,2)
E1=N(2)*N(2)
ZH=B/K0      $      RO=RK/K0
CALL FIELD(DS,K0,ZHM,RO,PZS,PXS,II,JJ)
CALL FIELD(DI,K0,ZH,RO,PZI,PXI,II,JJ)
CALL QV3(Q,II,JJ)
CALL RESULT(A0,SOM,II,JJ,IQ)
C=2.*E1/(E1+1.)
DO 10 J=1,JJ
DO 10 I=1,II
10 TOTL(I,J)=DS(I,J)-DI(I,J)+C*PZI(I,J)+PXI(I,J)+Q(I,J)*ST+SOM(I,J)
RETURN
END
```

```
SUBROUTINE QV3(HE,I,J)
COMMON /MAIN1/N(3),H,EPSR(3),RK
COMMON /MAIN2/B,P,T,CT,ST,CP,SP,CP2,SP2
DIMENSION HE(3,2),T1(3,2),T2(3,2)
COMPLEX N,C,HE,T1,T2,K,E,E1,J
PI=3.141592653      $      J=(0.,1.)
E1=N(2)*N(2)
K=(E1/(E1-1.))*(-.61593151-.5*J*PI+CLOG(N(2)))
C=(N(2)*N(2)-1.)/(N(2)*N(2)+1.)
E=(E1-1.)*C/2.
R=SQRT(B*B+RK*RK)
AA=ALOG(R*B)
R3=1./R**3      $      R5=1./R**5      $      RB1=1./(R*B)
RB2=RB1*RB1      $      RR=RB1/R      $      RB=(2.*R+B)*R3*RB2
T1(1,1)= C*(R3-3.*R5*(RK*CP)**2+.5*((B*CP/R)**2+SP**2)/R)
T1(2,1)=-C*RK*RK*SP2*(1.5*R5+.25*R3)
T1(3,1)=-C*RK*CP*(RR+3.*R5+.5*(R*R3-AA))
T1(1,2)=C*RK*RK*SP2*(.5*RB+.25*RR)
T1(2,2)=C*(RR-RB*(RK*CP)**2-.5*(AA+RR*(RK*CP)**2))
T1(3,2)=(0.,0.)
T2(1,1)=E*RB1*(B*CP*CP/R+SP*SP)
T2(2,1)=-E*SP2*(RK*RB1)**2/R
T2(3,1)=E*RK*CP*(-2.*RR+AA+B*RB1+K)
T2(1,2)=0.5*E*SP2*(RK*RB1)**2
T2(2,2)=-E*(AA+RB1*(R*CP*CP+B*SP*SP)+K)
T2(3,2)=(0.,0.)
DO 20 JJ=1,J
DO 20 II=1,I
20 HE(II,JJ)=T1(II,JJ)+T2(II,JJ)
RETURN
END
```

## SUBROUTINE CORREC(X,F,II,JJ)

C THIS SUBROUTINE IS USED WHENEVER A QUASI-STATIC CALCULATION IS  
 C NEEDED. AFTER THE INTEGRATION HAD REACHED CERTAIN LIMIT (ALPHA0)  
 C AS DESCRIBED IN SUBROUTINE (RESULT) THIS SUBROUTINE WILL BE EXECUTED  
 C TO GET THE REMAINDER OF THE INTEGRATION IN AN APPROX. FORM.  
 C THESE APPROX. HAVE BEEN SHOWN IN SECTION 4.2 , EQS. (50) AND (54)  
 C OF THE REPORT.

```

COMMON /MAIN1/N(3),H,EPSR(3),RK
COMMON /MAIN2/B,P,T,CT,ST,CP,SP,CP2,SP2
DIMENSION F(3,2),T1(3,2),T2(3,2),T3(3,2)
COMPLEX N,E1,F,J,K1,K2,T1,T2,T3,K3
E1=N(2)*N(2)      $  J=(0.,1.)      $  PI=3.141592653
K2=(E1-1.)/4.      $  K1=-2.*E1/(E1+1.):**2
K3=- (3.*E1+1.)*((E1-1.)/(E1+1.))**2/8.
R=SQRT(B*B+RK*RK)
BR=1./(R+B)      $  RR=BR/R
C=-0.11593151*ALOG(X)
AL=ALOG(R+B)      $  E=EXP(-X*B)
T1(1,1)=K1*RK*CP*CT*RR
T2(1,1)=K2*((-1.+(1.-B/R)*CP*CP)*BR+B*(AL+C)-R*E/X)*ST
T3(1,1)=2.*K3*(B*CP*CP/R*SP*SP)*BR*ST
T1(2,1)=K1*SP*CT*RK*RR
T2(2,1)=0.5*K2*SP2*(R-B)*RR*ST
T3(2,1)=-K3*SP2*ST*(RK*BR)**2/R
T1(3,1)=K1*(1./R*(X+1./X)*E+B*(AL+C)-R)*CT
T2(3,1)=K2*RK*CP*ST*RR
T3(3,1)=K3*CP*ST*RK*(-2.*RR*AL+B*BR*C)
T1(1,2)=-K1*RK*SP*CT*BR
T2(1,2)=(0.,0.)
T3(1,2)=.5*K3*SP2*ST*(RK*BR)**2
T1(2,2)=K1*RK*CP*CT*BR
T2(2,2)=K2*(AL+C-E)*ST
T3(2,2)=-K3*ST*(AL+C*(R*CP*CP+B*SP*SP)*BR)
T1(3,2)=(0.,0.)
T2(3,2)=K2*RK*SP*ST*BR
T3(3,2)=(0.,0.)
DO 10 JN=1,2
DO 10 IN=1,3
10 F(IN,JN)=T1(IN,JN)+T2(IN,JN)+T3(IN,JN)
RETURN
END

```



## SUBROUTINE ASMPT(POLE,T,EH,II,JJ)

C THIS SUBROUTINE PERFORMS THE ASYMPTOTIC EVALUATION OF THE EM FIELD  
 C COMPONENTS USING STEEPEST DESCENT METHOD. SKY WAVE APPROX. IS  
 C PERFORMED BY SUBROUTINE (LARGR) AND GROUND WAVE SOLUTION IS  
 C CALCULATED USING SUBROUTINE (FACTOR). THE INPUTS ARE :  
 C (1) POLE WHICH IS THE POLE LOCATION IN THE ALPHA PLANE.  
 C (2) T IS THETA WHICH IS THE ANGLE GIVEN BY  $\text{ARCTAN}(RO/(Z+H0))$ .  
 C EH IS THE RETURNED ASYMPTOTIC FIELD. II AND JJ ARE VARIABLE DIMENS.

```

COMMON /MAIN1/N(3),H,E(3),RR,K0,ZHM
COMMON /MAIN2/B,PHI,TP
COMPLEX POLE,EH,SMR,S1,S2,DS,DI,PZS,PXS,PZI,PXI,N,G,GP,IJ,P
REAL K0
DIMENSION EH(II,JJ),SMR(3,2)
1,DS(3,2),DI(3,2),PZS(3,2),PZI(3,2),PXI(3,2),PXS(3,2)
IJ=(0.,1.)
GP=-IJ*CSQRT(POLE*POLE-1.)
20 X=SIN(T)      S      C=COS(T)
R=SQRT(RR*RR+B*B)
RO=RR/K0      S      ZH=B/K0
P=(1.-IJ)*CSQRT((1.-GP*C-X*POLE)*R/2.)
CP=CABS(P)
IF (CP.GE.7.5) GO TO 25

CALL FACTOR(T,X,C,POLE,R,SMR,II,JJ)

CALL FIELD(DS,K0,ZHM,RO,PZS,PXS,II,JJ)
CALL FIELD(DI,K0,ZH,RO,PZI,PXI,II,JJ)

DO 10 J=1,JJ
DO 10 I=1,II
10 EH(I,J)=DS(I,J)-DI(I,J)+SMR(I,J)
GO TO 30
25 CALL LARGR(T,EH,II,JJ)
30 RETURN
END

```

## SUBROUTINE FACTOR(TT,A,G0,AP,R,HE,KK,LL)

C THIS SUBROUTINE CALCULATES THE ASYMPTOTIC FORM OF THE EM FIELD  
 C IN THE AIR REGION TAKING INTO CONSIDERATION THE GROUND WAVE  
 C SOLUTION. TWO TERM APPROX. HAS BEEN USED OUT OF THE ASYMPTOTIC  
 C SERIES. FORWARD, CENTRAL AND BACKWARD DIFFERENCE METHOD HAS BEEN  
 C USED TO REPLACE THE DERIVATIVES IN THE SECOND TERM.

```

COMMON /MAIN1/N(3),H,E(3),RO
DIMENSION BESJ(2),BESY(2),U(3,2),V(3,2),S0(4,3,2),S1(4,3,2)
1,TR1(3,2),TR2(3,2),DS(3,2),DDS(3,2),SS(3,2),HE(KK,LL)
COMPLEX WB1,WB2,GG,U,V,S0,S1,CF,TR1,TR2,DS,DDS,SS,HE
COMPLEX N,AP,J,B,G12,GP,FR,H10,H11,F,F0,F1,W,P,W1
J=(0.,1.)      S      PI=3.141592653
RAP=REAL(AP*AP)
IF (RAP.LT.1.0) GO TO 17
GP=-J*CSQRT(AP*AP-1.)      S      GO TO 34
17 GP=CSQRT(1.-AP*AP)
34 B=(1.+J)*CSQRT((1.-GP*G0-AP*A)/2.)
FB=1.0
AB=AIMAG(B)
IF (AB.LT.0.0) FB=-1.0
P=FB*B*SQRT(R)

```

```

      G12=CEXP(J*R)
      W1=W(P)*FB
C-----
C      W(P)=EXP(-P*P)*ERFC(-J*P)
C-----
      WB1=W1/B      $      WB2=B*(J*W1*FB/(P*SQRT(PI)))
      CF=PI*(1.-J)*B*B*G12
      D=5.0E-04
      AD1=TT*D      $      AD2=TT-D
      DO 39 M=1,4
      IF (AD1.GE.1.570796.OR.AD2.LE.0.0)      GO TO 42
      IF (M.GE.4) GO TO 201
      AD=SIN(TT+FLOAT(M-2)*D)
      ID=0
      GO TO 88
42 IF (AD1.GE.1.0) GO TO 72
      ID=1      $      AD=SIN(TT+FLOAT(M-1)*D)      $      GO TO 88
72 ID=2      $      AD=SIN(TT-FLOAT(M-1)*D)
88 GA=SQRT(1.-AD*AD)      $      GG=-J*GA
40 X=AD*RO
      F=AD*CEXP(-J*X)/SQRT((1.+GA*G0+AD*A)*2.)
      CALL BEJY(X,BESJ,BESY,2,2)
      H10=BESJ(1)+J*BESY(1)      $      H11=BESJ(2)+J*BESY(2)
      F0=H10*F      $      F1=H11*F
      CALL UV(AD,GG,U,V,KK,LL)
      DO 22 L=1,LL
      DO 22 K=1,KK
      S0(M,K,L)=F0*U(K,L)
22 S1(M,K,L)=F1*V(K,L)
39 CONTINUE
201 CONTINUE
      IF (ID.GE.1) GO TO 85
C      CENTRAL DIFFERENCE
      DO 83 L=1,LL
      DO 83 K=1,KK
      DS(K,L)=(S0(3,K,L)-S0(1,K,L)+S1(3,K,L)-S1(1,K,L))/(2.*D)
      DDS(K,L)=(S0(3,K,L)-2.*S0(2,K,L)+S0(1,K,L)+S1(3,K,L)-2.*S1(2,K,L)
1+S1(1,K,L))/D**2
83 SS(K,L)=-J*G0*(S0(2,K,L)+S1(2,K,L))
      GO TO 106
85 IF (ID.EQ.2) D=-D
C      FORWARD OR BACKWARD DIFFERENCE
      DO 93 L=1,LL
      DO 93 K=1,KK
      DS(K,L)=(-3.*S0(1,K,L)+4.*S0(2,K,L)-S0(3,K,L)-3.*S1(1,K,L)
1+4.*S1(2,K,L)-S1(3,K,L))/(2.*D)
      DDS(K,L)=(2.*S0(1,K,L)-5.*S0(2,K,L)+4.*S0(3,K,L)-S0(4,K,L)
1+2.*S1(1,K,L)-5.*S1(2,K,L)+4.*S1(3,K,L)-S1(4,K,L))/D**2
93 SS(K,L)=-J*G0*(S0(1,K,L)+S1(1,K,L))
106 DO 57 L=1,LL
      DO 57 K=1,KK
      TR1(K,L)=CF*WB1*SS(K,L)
      TR2(K,L)=CF*WB2*(-2.*J*A*DS(K,L)+J*G0*DDS(K,L)+(J/B**2+.75)*
1SS(K,L))
57 HE(K,L)=TR1(K,L)+TR2(K,L)
      RETURN
      END

```

```

      COMPLEX FUNCTION W(Z)
C-----
C      W(Z)=EXP(-Z*Z)*ERFC(-I*Z)
C-----
      COMPLEX I,Z,Z1,Z2,ZS,S3,S4,P1,P3,K,K1,FR
      I=(0.,1.)
      X=REAL(Z)      $      Y=AIMAG(Z)
      IF (X.GT.3.9.OR.Y.GT.3.0) 10,100
10  P1=I*Z      $      ZS=Z*Z
      IF (X.GT.6.0.OR.Y.GT.6.0) GO TO 5
      W=P1*(.4613135/(ZS-.1901635)+.09999216/(ZS-1.7844927)
      1+.002883894/(ZS-5.5253437))
      RETURN
5  W=P1*(.5124242/(ZS-.2752551)+.05176536/(ZS-2.724745))
      RETURN
100 P=2./SQRT(3.141592653)
      Z1=-I*Z
      S3=Z1      $      S4=S3      $      Z2=Z1**2
      DO 120 J=1,200
      N=J-1
      A1=FLOAT(2*N+1)      $      A2=FLOAT(2*N**2+5*N+3)
      P3=S3*Z2*A1/A2
      S3=P3      $      P5=CABS(P3)
      IF ((N/2*2).NE.N) GO TO 122
      S4=S4-P3      $      GO TO 124
122 S4=S4+P3
124 IF (P5.LE.1.0E-09) GO TO 226
120 CONTINUE
226 K=(1.,1.)      $      K1=(1.,-1.)
      FR=K*S4*P/2.
      W=CEXP(-Z*Z)*(1.-K1*FR)
      RETURN
      END

```

## SUBROUTINE RROOT(ZERO,AP)

C THIS SUBROUTINE SEARCHES FOR THE SURFACE MODES THAT EXISTS WITHIN  
 C A LOSSY DIELECTRIC SLAB ABOVE A FINITELY CONDUCTING GROUND (REFER TO  
 C SECTION-3 OF THE REPORT). AT FIRST, THE REAL ROOTS OF A LOSSLESS  
 C DIELECTRIC SLAB ABOVE A PERFECTLY CONDUCTING SHEET, WILL BE SEARCHED.  
 C THESE ROOTS ARE OF TWO TYPES OF POLARIZATION, TM (EVEN) AND TE (ODD)  
 C AS GIVEN BY EQS (39) AND (40) OF THE REPORT. THE ROOTS ARE THEN,  
 C PLUGGED IN EQS (37) AND (38) RESPECTIVELY TO SEARCH FOR THE COMPLEX  
 C OF A LOSSY SLAB ABOVE A FINITELY CONDUCTING EARTH. UP TO 5 ROOTS ARE  
 C SEARCHED AND, THEN SEND BACK TO THE MAIN PROGRAM VIA THE VARIABLE  
 C (ZERO). IF MORE ROOTS EXISTS, THE DIMENSION OF (ZERO) SHOULD BE  
 C INCREASED. THE ROOT CLOSEST TO THE REAL AXIS IN THE COMPLEX ALPHA-  
 C PLANE WILL BE SENT THRU THE VARIABLE (AP). IF THE PROGRAM FAILS TO  
 C FIND ANY ROOT WITHIN A GIVEN INTERVAL AN ARBITRARY POLE LOCATION  
 C (.95,.15) WILL BE ASSIGNED FOR ALPHA. THE INPUTS ARE THRU THE  
 C COMMON BLOCK /MAIN3/. SIG(3) AND EPSR(3) REPRESENTS THE  
 C CONDUCTIVITIES AND RELATIVE DIELECTRIC CONSTANTS IN THE THREE MEDIA  
 C STARTING WITH REGIONS (1) AIR, (2) SLAB AND (3) EARTH.  
 C HESLAB WIDTH. OMEGA $\epsilon$  ANGULAR FREQ. IN RADIAN.  
 C OUTPUTS ARE;  
 C ZERO= ZEROES FOUND.  
 C AP= THE ROOT CLOSEST TO THE REAL AXIS IN THE COMPLEX ALPHA-PLANE.

```

COMMON /MAIN3/SIG(3),EPSR(3),H,OMEGA
DIMENSION ZERO(5)
COMPLEX ZERO,ZZ,AP
LOGICAL G
EXTERNAL FX,FY
PI=3.141592653
F2=H*SQRT(EPSR(2)-1.)
IN=INT(2.*F2/PI)+1
II=IN
X=FLOAT(IN)/2.      S      Y=FLOAT(IN/2)
IF (X.EQ.Y) GO TO 55
62 T1=FLOAT(IN-1)*PI/2.+1.0E-08
TT2=FLOAT(IN)*PI/2.-1.0E-05
T2=AMIN1(F2,TT2)
PRINT 65
65 FORMAT (1X,'ROOT OF TM TYPE MODES')
CALL ROOT(T1,T2,FY,X1,100,1.0E-05,100.,G)
IF (G) GO TO 105
RALPHA=SQRT(EPSR(2)-X1*X1/H/H)
PRINT 75,X1,RALPHA
IM=2
CALL ZROOT(IM,X1,ZZ,G)
IF (G) GO TO 4
ZERO(IN)=ZZ      S      GO TO 101
4 PRINT 79,ZZ
ZERO(IN)=(.95,.15)
105 PRINT 72,IN
101 IN=IN-1
IF (IN.LE.0) GO TO 15
55 T1=FLOAT(IN-1)*PI/2.+1.0E-05
TT2=FLOAT(IN)*PI/2.-1.0E-05
T2=AMIN1(F2,TT2)
PRINT 69
69 FORMAT (1X,'ROOT OF TE TYPE MODES')
CALL ROOT(T1,T2,FX,X1,100,1.0E-05,100.,G)
IF (G) GO TO 107
RALPHA=SQRT(EPSR(2)-X1*X1/H/H)
PRINT 75,X1,RALPHA
IM=1
CALL ZROOT(IM,X1,ZZ,G)
IF (G) GO TO 6
ZERO(IN)=ZZ      S      GO TO 109
6 PRINT 79,ZZ
  
```

```

      ZERO(IN)=(.95,.15)
107 PRINT 72,IN
109 IN=IN-1      S      GO TO 62
75 FORMAT (1X,*GAMA1 H1=*E13.5,3X*ALPHA REAL=*E13.5//)
72 FORMAT (1X,*REGION*I3.5X*NO REAL ROOTS HAVE BEEN FOUND*/)
79 FORMAT (1X*NO ROOTS ARE BEING FOUND OR IT DIDNT CONVERGE*,1X
1*Z=*2(2XE13.5)//)
15 IF (II.LE.1) GO TO 9
   AA=AIMAG(ZERO(1))
   DO 12 I=2,II
   AI=AIMAG(ZERO(I))
   IF (AA.LE.AI) GO TO 12
   IK=I      S      AA=AI
12 CONTINUE
   AP=ZERO(IK)      S      GO TO 16
9   AP=ZERO(1)
16 RETURN
END

```

```
SUBROUTINE ROOT(A,B,F,X,JMAX,E,E1,G)
```

```
C   THIS SUBROUTINE USES THE BISECTION METHOD TO SOLVE FOR ONE ODD
C   ROOT OF  $F(X) = 0$  ON THE INTERVAL (A,B). THE FUNCTION PASSED
C   THROUGH F MUST BE DECLARED EXTERNAL IN ALL CALLING PROGRAMS. E IS
C   INTERVAL OF UNCERTAINTY DESIRED FOR THE ROOT, AND MUST BE SMALLER
C   THAN THE STARTING INTERVAL.  $W = B - A$ . THE NUMBER OF BISECTIONS IS
C   DETERMINED BY  $NMAX = \text{LN}(W/E)/\text{LN}(2)$ . AFTER BISECTING, THE FUNCTION
C   VALUE IS COMPARED TO E1. IF  $\text{ABS}(F(X_0)) > E1$  THEN THE SUBROUTINE
C   PRINTS: DISCONTINUITY AT  $X = X_0$ . A RANDOM SEARCH OCCURING JMAX
C   TIMES IS USED TO LOOK FOR A CHANGE OF SIGN IF  $\text{SIGN}(F(A)) =$ 
C    $\text{SIGN}(F(B))$ .
C   DISCONTINUITY AT  $X =$  . A RANDOM SEARCH OCCURING JMAX TIMES IS
C   USED TO LOOK FOR A CHANGE OF SIGN IF  $\text{SIGN}(F(A)) = \text{SIGN}(F(B))$ .
C   A PLOT OPTION IS AVAILABLE THROUGH ENTRY POINT PLOT
C   THAT WILL PLOT THE FUNCTION F ON THE INTERVAL (A,B) AT JMAX
C   EQUALLY SPACED POINTS. WHEN USING THE PLOT ENTRY, JMAX MUST BE
C    $\leq 100$ , AND THE FOLLOWING SUBROUTINES ARE NEEDED: KPXNYN, KPRINT,
C   AND KSC120.
```

```
LOGICAL G
REAL LN2
DIMENSION Y(3)
```

```
C   QUESTION: DOES  $F(A) = 0$ .
```

```
Y1=F(A)
IF(Y1.NE.0.) GOTO 10
X=A
GOTO 80
```

```
C   QUESTION: DOES  $F(B) = 0$ .
```

```
10 Y2=F(B)
IF(Y2.NE.0.) GOTO 20
X=B
GOTO 80
```

```
C   QUESTION: ARE THE SIGNS OF  $F(A)$  AND  $F(B)$  DIFFERENT.
```

```
20 I1=SIGN(1.,Y1)
I2=SIGN(1.,Y2)
W=B-A
IF(I1.NE.I2) GOTO 60
```

```
C   SEARCH FOR A CHANGE IN SIGN.
```

```
DO 30 J=1,JMAX
X=A+RANF(0.)*W
I3=SIGN(1.,F(X))
IF(I3.NE.I1) GOTO 50
JM=J
30 CONTINUE
PRINT 40
40 FORMAT(1X*NO CHANGE OF SIGN FOUND*/)
G=JM.EQ.JMAX
RETURN
50 B=X
```

```
C   DETERMINE NUMBER OF BISECTIONS
```

```
60 LN2=0.693147181
NMAX=ALOG(W/E)/LN2+1.
Y(2+I1)=A
```

```

      Y(2-I1)=B
C     BEGIN BISECTION

      DO 70 N=1,NMAX
      X=(Y(1)+Y(3))/2.
      Y3=F(X)
      IF(Y3.EQ.0.) GOTO 80
      I3=SIGN(1.,Y3)
70    Y(2+I3)=X
80    IF(ABS(F(X)).LE.E1) GOTO 85

C     CONVERGENCE TO A DISCONTINUITY

      PRINT 82,X
82    FORMAT(1X*DISCONTINUITY AT X = *E12.4/)
      G=ABS(F(X)).GT.E1
      RETURN

C     CONVERGENCE TO A ROOT

85    PRINT 90,X
90    FORMAT(1X*ONE ODD ROOT AT X = *E12.4/)
      G=ABS(F(X)).GT.E1
      RETURN

      END

```

#### FUNCTION FX(Z)

```

C     EQ. (40) ,SECTION 3 OF THE REPORT. TE (ODD) TYPE ROOTS WILL BE
C     SEARCHED.

```

```

      COMMON /MAIN3/S(3),E(3),H
      FX=Z*TAN(Z)*SQRT((E(2)-1.)*H*H-Z*Z)
      RETURN
      END

```

#### FUNCTION FY(Z)

```

C     EQ. (39) ,SECTION 3 OF THE REPORT. TM (EVEN) TYPE ROOTS WILL BE
C     SEARCHED.

```

```

      COMMON /MAIN3/S(3),E(3),H
      E1=E(2)
      FY=(Z/E1)*TAN(Z)-SQRT((E1-1.)*H*H-Z*Z)
      RETURN
      END

```

## SUBROUTINE ZROOT(IT,X,Z,GGG).

C THIS SUBROUTINE WILL SEARCH FOR THE COMPLEX ROOT OF A LOSSY SLAB  
 C ABOVE A FINITELY CONDUCTING EARTH. BY USING THE REAL ROOT FOUND FROM  
 C THE SUBROUTINE (ROOT) AND SENT THRU THE VARIABLE (X) TO THIS PROGRAM  
 C FROM THE SUBROUTINE (PROOT) . A COMPLEX ROOT WILL BE SEARCHED FOR  
 C THE SITUATION OF A LOSSY SLAB ABOVE GROUND . THE VARIABLE (IT)  
 C DETERMINE IF THE ROOT IS IN THE TM OR TE CATAGORIES. (Z) IS THE  
 C RETURNED COMPLEX ROOT .(GGG) IS A LOGICAL STATEMENT ,IF IT IS TRUE  
 C NO COMPLEX ROOT IS FOUND OR PROBABLY FAILED TO CONVERGE TO A ROOT.  
 C OTHERWISE, (GGG) IS FALSE AND ,THUS, A COMPLEX ROOT IS FOUND.

```

COMMON /ZZZZ/N(3),H,EPSR(3)
COMMON /MAIN3/S(3),E(3),HH,OMEGA
COMPLEX N,CX,CENTR,ZERO,Z,CY,ALPHA
EXTERNAL CX,CY
DIMENSION SIGMA(3)
LOGICAL GG,GGG
PI=3.141592653
EPS0=8.854E-12
FREQN=OMEGA/2./PI
H=HH
DO 99 JJ=1,3
  SIGMA(JJ)=S(JJ)
99 EPSR(JJ)=E(JJ)
  DO 12 J=1,3
    12 N(J)=CSQRT(EPSR(J)+(0.,1.)*SIGMA(J)/OMEGA/EPS0)
    CENTR=X
    IF (IT.EQ.2) GO TO 115
    CALL CROOT(CX,CENTR,ZERO,TT,GG)
    IF (GG) GO TO 66
    GO TO 90
  115 CALL CROOT(CY,CENTR,ZERO,TT,GG)
    IF (GG) GO TO 66
  90 PRINT 88,FREQN,(N(J),J=1,3)
  88 FORMAT (1X,*FREQ.=*E11.3/20X*N0=*F7.3,*J*F9.4/,
    120X*N1=*F7.3,*J*F9.4/,20X*N2=*F7.3,*J*F9.4//)
    ALP,A=CSQRT(-ZERO*ZERO/H/H+N(2)*N(2))
    PRINT 18,ALPHA
  18 FORMAT (1X,*ALPHA=*E13.5,*J*E13.5/)
  109 Z=ALPHA
    GGG=TT.GT.1.0E-5
    RETURN
  66 Z=CSQRT(-ZERO*ZERO/H/H+N(2)*N(2))
    PRINT 67,Z,TT
  67 FORMAT (1X,*IT FAILED TO CONVERGE*,4X*ZERO=*E13.5,*J*E13.5,
    14X*TEST=*E13.5/)
    GGG=TT.GT.1.0E-5
    RETURN
  END

```



## SUBROUTINE CROOT(CF,Z0,ROOT,TEST,G)

C IN THIS SUBROUTINE A NEWTONS METHOD PLUS A HALVING TECHNIQUE WILL  
C BE USED TO SEARCH FOR COMPLEX ROOTS.

```

COMMON /PRIME/DCF
COMPLEX CF,DCF
COMPLEX ROOT,F,DF,Z0,Z1,Z01
LOGICAL G
J=0
I=0
F=CF(Z0)      $      DF=DCF
TEST0=CABS(F)
IF (TEST0.GT.1.0E-05) GO TO 25
TEST1=TEST0    $      GO TO 100
25 Z1=Z0-F/DF
30 F=CF(Z1)      $      DF=DCF
TEST1=CABS(F)    $      Z01=Z1-Z0      $      Z0=Z1
IF (TEST1.LE.1.0E-05) GO TO 100
IF (J.GE.50) GO TO 100
J=J+1
IF (TEST1.LE.TEST0) GO TO 25
CAB=CABS(Z01)
IF (CAB.LE.1.0E-05) GO TO 100
Z1=Z0-Z01/2.    $      I=I+1
IF (I.GE.10) GO TO 100
GO TO 30
100 ROOT=Z0
TEST=TEST1
G=TEST.GT.1.0E-05
RETURN
END

```

## COMPLEX FUNCTION CX(Z)

C EQ. (38) ,SECTION 3 OF THE REPORT.

```

COMMON /PRIME/DCX
COMMON /ZZZZ/N(3),H,EPSR(3)
COMPLEX DCX
COMPLEX N,Z,E1,E2,GN2,U,HN
COMPLEX G0,G2,DG0,DG2,CS,CC,GZ
H2=H*H      $      E1=N(2)*N(2)      $      E2=N(3)*N(3)
U=-Z*Z+E1*H2
HN=E2*H2
G0=CSQRT(U-H2)
G2=CSQRT(U-HN)
CS=CSIN(Z)      $      CC=CCOS(Z)
DG0=-Z/G0      $      DG2=-Z/G2
GZ=G0*G2/Z-Z
CX=GZ*CS/CC+G0+G2
DCX=GZ/CC/CC+(DG0*G2/Z+DG2*G0/Z-G0*G2/Z/Z-1.)*CS/CC+DG0+DG2
RETURN
END

```

## COMPLEX FUNCTION CY(Z)

C EQ. (37) ,SECTION 3 OF THE REPORT.

```

COMMON /PRIME/DCY
COMMON /ZZZZ/N(3),H,EPSR(3)
COMPLEX DCY
COMPLEX N,Z,E1,E2,GN2,U,ZZ,HN
COMPLEX G0,G2,DG0,DG2,CS,CC,GZ
H2=H*H      $      E1=N(2)*N(2)      $      E2=N(3)*N(3)
U=-Z*Z+E1*H2
HN=E2*H2
G0=CSQRT(U-H2)
G2=CSQRT(U-HN)
67 ZZ=Z/E1      $      GN2=G2/E2
CS=CSIN(Z)      $      CC=CCOS(Z)
DG0=-Z/G0      $      DG2=-Z/G2
GZ=G0*GN2/ZZ-ZZ
CY=GZ*CS/CC+G0*GN2
DCY=(-G0*GN2/ZZ/Z+(DG0*GN2+G0*DG2/E2)/ZZ-1./E1)*CS/CC
1+GZ/CC/CC+DG0*DG2/E2
RETURN
END

```